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APPLIED ELECTRICITY
FOR
PRACTICAL MEN

BY
ARTHUR J. ROWLAND
PROFESSOR OF ELECTRICAL ENGINEERING AT THE DREXEL INSTITUTE,
PHILADELPHIA, PA.

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PREFACE

There are many books written for the purpose of imparting electrical engineering knowledge without demanding of the reader as a necessary prerequisite, a considerable acquaintance with mathematics and science. They appear, however, to be of two types. One attempts to cover the whole range from electrostatics, through current electricity to wireless telegraphy with the result that it is extremely superficial and useless for practical purposes. The other deals almost wholly with principles, and stops off just where application to practical apparatus begins.

This volume has been in the process of making during twenty years' experience in teaching Applied Electricity to practical electrical workers; to men who expect to make direct application of the principles given them in the class room to their daily work with commercial circuits and machinery. It is written wholly from the standpoint of the one who puts up and operates electric circuits and apparatus. It does not touch problems of apparatus design. Pure theory is avoided, except as it has direct bearing upon practical matters. The principles stated and the explanations of apparatus which are offered are only such as are necessary in order to present essential elements. They can be elaborated by the instructor as much as he may see fit.

Every teacher understands the importance of numerical problems in order to make clear the principles and performance of apparatus. It is with this in mind that the set of problems found at the end of each chapter has been made up. Even though the computations demanded in the solution of many of the problems of this book are not required in everyday practical work, it *is* important to understand *how* a thing works; and unless one can make a computation regarding it and figure out a numerical result, no clear conceptions have been secured.

345076

The book is offered to the public in the hope that it may fill a need in connection with the study of Applied Electricity in trade and industrial schools; and that the explanations may be helpful to electrical workers everywhere.

A. J. R.

Philadelphia, Pa.
September. 1916.

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APPLIED ELECTRICITY
FOR
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CHAPTER I

FUNDAMENTAL PRINCIPLES

1. Electric Current.—When observing many familiar phenomena connected with the production of light or the generation of motive power, we understand that the effects observed are due to electric current. At the outset it would seem as though an explanation should be given of what this is. The words suggest the flow of something. But what is flowing, what electric current is, or what electricity is no one knows; so the mystery must stay unsolved. There are a great many other things equally mysterious in everyday life. A water current is a commonplace thing; it is the flow of a quantity of water. If we ask a chemist, he might tell us that water is a combination of two gases bound together according to a fixed proportion in every molecule; but this does not help us to know what water currents are. Rather we must get to know how they can be produced, why they flow, in what sorts of apparatus they can be used. And if this is supplemented by a practical experience in handling moving water and the apparatus in which it moves, a real knowledge of the subject has been obtained. Just what water is makes little difference.

So it is with electric currents; only by becoming familiar with the laws which govern them, and the apparatus in which they are used, can we come to know about them. The purpose of the study of electricity is this very thing, and not an examination into the nature of the mysterious current itself.

2. Kinds of Current.—Electric currents may be of different kinds. They do not differ in nature, but in the method of flow or in the purpose to which they are applied. A *direct current* or continuous current is one which is fixed in amount and constant in direction, while the circuit is closed and after current is established. An *alternating current* is one which reverses its direction at fixed intervals, while between the times of reversal it grows from nothing to larger and larger values until it reaches a maximum, after that diminishing in amount to nothing. These two sorts of current, direct and alternating, are the important ones, the ones which every electrician knows about. Other classifications may be made, such as: (*a*) interrupted current, one which is stopped off and started again; (*b*) pulsating current, a direct current which rises to larger value and falls off to a smaller one over and over as time goes on; (*c*) oscillatory current, one which reverses direction like an alternating current but whose maximum values become less and less until no current at all is flowing. Currents may also be classed according to their availability. Thus one might be adapted to operate a certain kind of motor, but unavailable for electroplating; one might be useful to discharge a blast, but not to run any motor.

3. The Unit of Current.—In order to learn anything about electric current we must be able to talk of its amount. This requires a unit in which to measure it. The name of the unit is the *ampere*. We learn how much an ampere of current is by observing what it can do. No formal definition can give us an intelligent conception, however much value it may have for purposes of absolute measurement or standardization.[1] If a definition of a dollar as a unit of the measurement of money were required, it would be very hard to form one which would give a satisfactory idea to a person who had no experience in the use of dollars and so did not know by actual use what a dollar was or what it could do.

The things that current can do, the effects of current as usually stated, are lighting, heating, producing motion, making magnets and magnetic fields, producing chemical actions.

---

[1] The legal and scientific definition of the ampere in the United States is: "The unit of current shall be what is known as the international ampere, which is one-tenth of the unit of current of the centimeter-gram-second system of electromagnetic units, and is the practical equivalent of the unvarying current, which, when passed through a solution of nitrate of silver in water in accordance with standard specifications, deposits silver at the rate of one thousand one hundred and eighteen millionths of a gram per second.

It is only by observation of these effects and their magnitude that we know anything about the presence of current and its amount. All measuring instruments use one of these effects as a means of determining how much current is flowing. An instrument which measures amperes by the direct reading of a deflected pointer along a scale is an *ammeter*. A *galvanometer* is an instrument to indicate flow of current, in which the motion of some part gives the means of telling that current is flowing. It has no direct reading scale and is used for many other purposes besides the measurement of current.

The amount of current flowing in ordinary apparatus might be:

To light an ordinary 20-cp. incandescent lamp	0.25 to 0.5 amp.
To light a common enclosed arc lamp	5.0 amp.
To heat a 5-lb. pressing iron	4.0 to 5.0 amp.
To operate a desk fan motor	0.5 to 1.5 amp.
To start an interurban train	200.0 to 2000.0 amp.
To work the magnets of main line telegraph	0.015 amp.
To electroplate an electrotype for a page of this book	0.5 to 1.5 amp.

Some currents are so small that another unit, the milampere, is made use of. One thousand milamperes make an ampere.

In the supply systems of office buildings and industrial plants a thousand amperes or so is as much as will ever be supplied; in a few large plants or in very large central station distributing systems the total flow of current may at times rise to nearly 100,000 amp. These figures are mentioned in order that from the beginning the magnitude of commercial currents may be known before actual handling of electrical apparatus has given one a more intimate knowledge. It should be clear from the start that relative values are of most importance; for example, that an arc lamp uses ten times as much current as an incandescent lamp.

4. Conductors and Insulators.—All material bodies may be classified by observing that current passes through some and will not pass through others. Those through which current passes are called conductors; those through which it will not pass are called insulators. Metals and most solutions of chemical salts are conductors. Since no hard and fast classification into conductors and insulators is possible, the following table is inserted:

Good conductors	Fair conductors	Poor conductors	Insulators
Silver.	Carbon.	The human body.	Slate.
Copper.	Acid solutions.	Linen.	Porcelain.
Aluminum.	Alkali solutions.	Cotton.	Marble.
Zinc.	Salt solutions.	Paper.	Sealing wax.
Iron (wrought).	Moist earth.	Wood.	Rubber.
Nickel.		Water.	Shellac.
Tin.			Paraffine.
German silver.			Glass.
Iron (cast).			Air.
Mercury.			

Moisture changes many insulators into poor conductors, and poor conductors into fair conductors. At elevated temperatures many insulators become conductors.

When current passes through metallic or carbon conductors it does so without altering them in any way. When passing through most non-metallic conductors, chemical decomposition occurs.

Conductors are used to form the paths in which current is to flow; insulators to hold the current in the desired paths. Hence the importance and value of insulated wire.

5. Electrical Diagrams.—In order to understand any practical problem relating to the flow of current, it is necessary to be able to draw a picture which shall represent the apparatus in use and the paths in which the current flows. For this purpose certain conventional signs have been adopted so that no picture need be drawn and yet the meaning of the diagram is perfectly clear. A few of the conventions are here shown. Others will appear later in the book and will generally be self-explanatory.

Conventions somewhat different from these have been adopted by the National Electrical Contractors Association for use in wiring plans, but they are not well adapted to general diagrammatic work.

In diagrams shown in any books, care is taken to make the arrangement neat and clear. Everyone who makes diagrams should use care to give them as neat an appearance as possible. In Figs. 2, 3, and 4 are examples of what is meant.

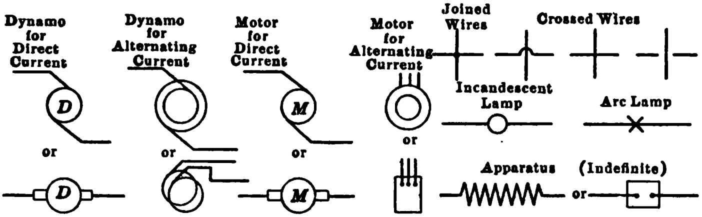


FIG. 1.

6. The Electric Circuit.—An electric circuit is a conducting path including a source of current. The various pieces of apparatus in it are generally connected by insulated wires. The nature of the circuit and the interconnections are best shown by diagrams. One sort of circuit is that in which the various devices are connected in series. In such a circuit the current flows on through one thing after another (Fig. 2). The + mark on the dynamo indicates the terminal out of which the current flows (the positive or plus terminal). The − mark indicates the one into which it returns (the negative or minus terminal). Another way to connect apparatus is as shown in Fig. 3. In this case the lamps are said to be connected in parallel or multiple. In this

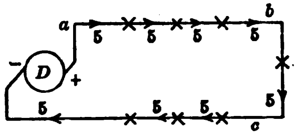


FIG. 2.

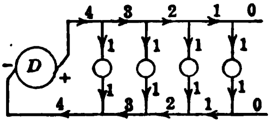


FIG. 3.

case the current from the + terminal of the dynamo flowing out divides, passing through all four lamps as different branches of the one circuit.

The current is the same at every point of a circuit. This will be clear from either Fig. 2 or 3. In Fig. 3 the four lamps are branches of the same circuit. Current will only flow in a complete conducting path. This would be called a *closed circuit.* In Fig. 2 the conducting path is continuous through wires, lamps, and dynamo. Five amperes is flowing all along this path. To stop the flow of current the circuit may be opened at *a*, *b*, or *c*, or anywhere else. In every case the current will stop flowing in the whole circuit. An *open circuit* is one in which the conductor is not continuous at some point or points. This may be the result of deliberate action or due to some fault which has developed.

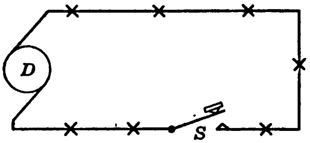


Fig. 4.

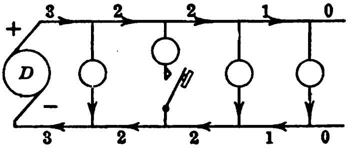


Fig. 5.

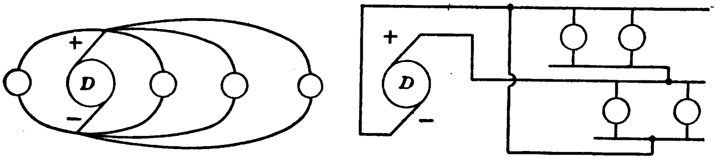


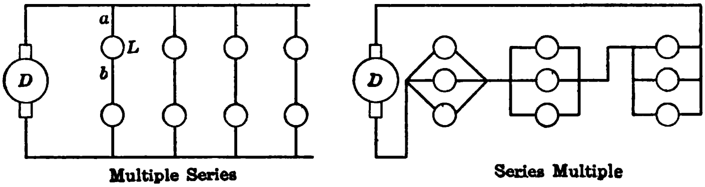
Fig. 6.

Usually when a circuit is opened it is due to the separation of certain conductors by means of a switch. This act would be called opening or breaking the circuit. The reverse process is called closing or making the circuit. In Fig. 4 at *S* the circuit has been broken and no current flows. In Fig. 5 a current path has been broken also; compare Fig. 3 and Fig. 5.

Fig. 6 shows two diagrams for lamps connected in parallel.

Either of them is the exact equivalent electrically of Fig. 3, which might indeed be called a simplified diagram of either of them. In practical work actual circuits are often so complex that simplified diagrams are necessary in order to understand them. The reader will do well to reproduce the diagrams of Fig. 6, as shown, and mark on them the amount and direction of current flowing at every point in order to verify the facts above stated.

Sometimes devices are connected in multiple-series, or series-multiple (see Fig. 7). Sometimes they are connected into networks (see section 77). A *short-circuit* is one which includes no useful path for current from dynamo or battery; or referring to a certain piece of apparatus, its terminals are joined directly by a short piece of circuit. Thus, in Fig. 7, if a wire were connected directly from *a* to *b* the lamp *L* would be short-circuited.



Multiple Series **Series Multiple**

FIG. 7.

7. Resistance.—Some conductors are better than others, as already noted. This difference is inherent in them for it is a property they have as much as color or mechanical strength. The best conductor is said to have the least resistance; the poorer a conductor is, the more resistance it is said to have. The resistance of a conductor is fixed in amount without regard to whether current flows in it or not, and without regard to the amount of current flowing. It varies some with change in the temperature of the conductor, as will be later explained.

The important things to know about resistance are the following:

The Resistance of a Conductor Varies with its Length.—The longer a conductor the greater its resistance; doubling the length doubles the resistance; reducing the length to quarter the former amount reduces the resistance to quarter of what it was before. The resistance is the same no matter whether the conductor is coiled up or stretched out in a straight line.

The Resistance of a Conductor Varies Inversely with its Cross-section.—By cross-section is meant the actual area brought to view if the conductor is cut directly across. Thus, suppose we had two wires, one having a diameter of 1/10 in. and the other 1/5 in. They are cut off square across and in Fig. 8 we see the ends to an enlarged scale. Wire *A* has 1/4 the section of wire *B*. The cross-section of a conductor is independent of the shape of the section, however. Thus, in Fig. 9, *C* shows four wires laid together, each one the size of *A*. The cross-section of cable *C* is the same as of *B*. At *D* is shown a square conductor which has the same cross-section as *B*; its side is 0.1772 in. The term cross-section implies no particular shape then. Referring further to Fig. 8, the wire *A* has four times the resistance per foot of wire *B*, because it has 1/4 the section. This is the significance of the term "varies inversely" used above. A cable made of 19 wires all alike would have a resistance 1/19 as much as of one wire alone.

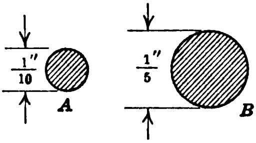


FIG. 8.

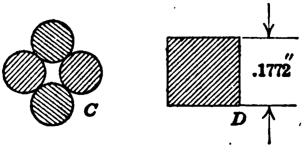


FIG. 9.

The Resistance of a Conductor Varies with the Material of the Conductor.—Here the inherent property of the material comes in. There is nothing to guide except certain rough rules like: The resistance of metals is less than that of other conductors; the resistance of a metallic alloy is greater than that of any one of the components which make it up. In the table on page 4 the conductors were set down in the order of their resistance, the best conductor being at the head of the list. Some approximate values of relative resistance are given below. It would be well to memorize the numbers for copper, iron, and german silver.

Material	Relative resistance
Copper	1
Aluminum	1.7
Zinc	3.6
Wrought iron	6
Lead	13
Cast iron	64
Mercury	65
18 per cent. german silver (copper, nickel and zinc)	20–21
Manganin (copper, manganese and nickel)	25
Water with 25 per cent. sulphuric acid	300,000
Salt water (saturated)	8,000,000
Sulphate of copper	11,000,000
Sulphate of zinc	16,000,000
Pure water	50,000,000,000
Glass	10,000,000,000,000,000,000
Hard rubber	200,000,000,000,000,000,000

8. Unit of Resistance.—The unit of resistance measurement is the *ohm*. When very small resistances are measured the *microhm* is used as the unit of measurement. A microhm is a millionth of an ohm. When very large resistances are measured the *megohm* is used as the unit. A megohm is a million ohms. Until one gets used to estimating resistance by the same feeling which enables a mechanic to estimate the mechanical resistance of a stick of timber or a bolt, this cannot mean very much. A formal scientific definition can easily be given,[1] but for everyday purposes another basis is very useful.

9. Resistance of Wires.—Wires are supplied to the market in regular sizes, each one of a specified diameter. In the B. & S. or American wire gage, if one starts with any size and goes toward smaller sizes, at the third size the section will be half that from which one started. Thus No. 15 has half the section of No.

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[1] The unit of resistance shall be what is known as the international ohm, which is *substantially equal* to one thousand million units of resistance of the centimeter-gram-second system of electromagnetic units, and is represented by the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice fourteen and four thousand five hundred and twenty-one ten-thousandths grams in mass, of a constant cross-sectional area, and of the length of one hundred and six and three-tenths centimeters.

12; or No. 1 has twice the section of No. 4. No. 10 copper wire measures 1 ohm per 1000 ft. of length, and is $\frac{1}{10}$ in. in diameter. With this as a basis and the information of the preceding paragraph, many useful practical problems can be solved. (Further details regarding wire and wire gage are found in Chap. XVIII.)

Example.—What is the resistance of 250 ft. of german silver wire No. 19 size? No. 10 copper wire 1000 ft. long has 1 ohm resistance, so 250 ft. would have 0.25 ohm resistance. 250 ft. of No. 13 would measure 0.5 ohm.; of No. 16, 1 ohm; of No. 19, 2 ohms. But german silver wire has 20 times the resistance of copper wire. Hence the resistance of 250 ft. of No. 19 german silver wire would be 2 × 20 = 40 ohms.

10. Circuit Resistance.—Since all conductors have resistance, every electrical circuit must have it. Resistance is found in every piece of apparatus and in every connecting wire. Three sorts of resistance might be mentioned: (1) That which cannot be helped since it comes in as part of necessary apparatus; (2) that which is useless and should be avoided; (3) that which is used to regulate or control the amount of current flowing in a circuit as is further explained in the next chapter.

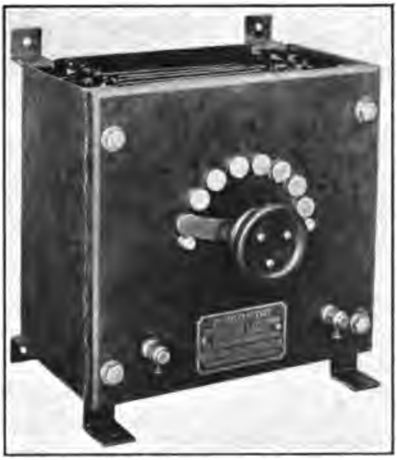

Fig. 10.

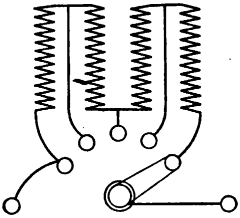

Fig. 10*a*.

Examples of each of these sorts of resistance may be given.

(1) If an incandescent lamp is required, it must be taken along with its resistance (200 ohms or more). A dynamo to supply current must be built with a number of coils of wire on it through which the current flows, and their resistance is unavoidable. (2) A line of connecting wire is made unnecessarily long; or at some point wires are twisted together, thus making an imperfect perhaps almost an open circuit, and so more resistance than necessary is introduced. (3) In a very great number of practical circuits resistance is deliberately put into a circuit. It may take the form of a closed box (a *resistance box*) within which is some conductor arranged compactly. It may be, for example, an iron strip folded together with mica set between the layers. A resistance box is diagrammatically represented in Fig. 1 as apparatus (indefinite). It might be a *rheostat* which is an adjustable resistance. This may take many forms. Fig. 10 shows a cut of one, and Fig. 10*a* a diagram for one. If the handle is revolved the sweep arm moving over the contacts reduces or increases the amount of resistance in the circuit in a manner which will be clear from the diagram. Fig. 11 shows a water rheostat, another form, in which water with washing soda dissolved in it is the path for current, and the resistance is varied by changing the distance between the plates.

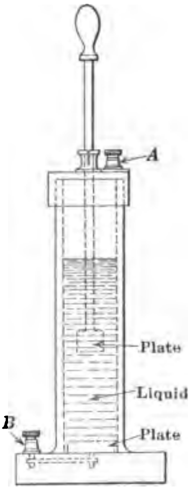

FIG. 11.

11. Combinations of Resistance.—From the statements of paragraphs 7 and 9, certain simple but very important deductions can be made.

Suppose we have a coil of No. 10 insulated copper wire 5000 ft. long. This will measure 5 ohms resistance. If we cut this into two parts, one 2000 ft. long and the other 3000 ft. long, the first would measure 2 ohms and the second 3 ohms. If these are connected in series they make a continuous wire of 5 ohms resistance. Now let each of the coils be put in a box provided with binding posts[1] (Fig. 12). Each one becomes to its user merely 2 ohms or 3 ohms, so that if from either or both boxes the coil of No. 10 copper wire were removed and something equivalent in copper, iron, or german silver substituted, no difference at all would be found in the circuit. We might put into one box, instead of 2000 ft. of No. 10 copper, 500 ft. of No. 16 copper wire or 1 ft. 6¾ in. of No. 25 german silver wire, for each would have the same resistance and would be a complete substitute. Hence we find that the *combined resistance of a number of devices connected in series is the sum of their individual resistances*, no matter what is the nature of each one.

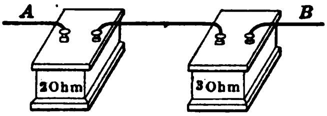

Fig. 12.

Example.—I have a miniature incandescent lamp (resistance 5 ohms), a coil of insulated german silver wire wound on a spool (resistance 10 ohms), a signalling magnet whose coil of copper wire has a resistance of 8 ohms, and I use some copper wires to connect these in series, amounting to ½ ohm. The total resistance would be 23½ ohms.

Now let us remind ourselves of the statements of section 7 regarding the effect of change of section of a conductor on its resistance, and in particular of the fact that the cable *C* of Fig. 9 has ¼ the resistance of *A*. Suppose we have a No. 10 copper wire 1000 ft. long laid out in a straight run. If we lay another No. 10 wire 1000 ft. long beside it, the section provided for the flow of current is doubled, and so the resistance is halved. The two together have a resistance of ½ ohm. This is independent of whether the wires are insulated or uninsulated; a connection at the ends only is required. But suppose each wire were coiled and placed in a box as in Fig. 13. The combined resistance *A* to *B* is the same (½ ohm) as in the case at the left of the figure where the insulated wires have been broken in the figure but are to

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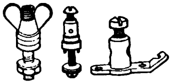


[1] Binding posts commonly form the fixed terminals of electrical apparatus. They are so made as to afford ready means of connecting circuit wires to apparatus. They are usually made of brass and have many forms, some of which are shown in the figures here.

represent two which are continuous straight away for 1000 ft. It will be obvious that once things are in the shape shown in the right hand part of this figure it is a matter of indifference, so far as the resistance from A to B is concerned, whether copper wire or any other sort is in either of the boxes, or what number of feet of wire of the particular size used is there, if in each box the right length of conductor is put to make 1 ohm. From these considerations we see that if two things having the same resistance are connected in parallel their combined resistance will be half that of either one, or *if any number of pieces of conducting apparatus, all having the same resistance, are connected in parallel, the combined resistance of the lot is the resistance of one divided by the number of pieces of apparatus so connected.*

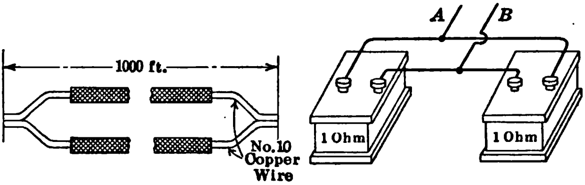


Fig. 13.

Example.—In Fig. 14 are shown 10 incandescent lamps, each of which has a resistance of 220 ohms. If in comparison with this resistance that of the connecting wires may be neglected: (*a*) what is the resistance from X to Y, and (*b*) what would it be if half of them were disconnected?

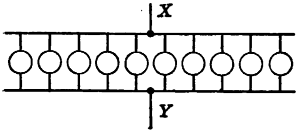


Fig. 14.

(*a*) $\frac{220}{10} = 22$ ohms. (*b*) $\frac{220}{5} = 44$ ohms.

A more general method of computing the joint resistance of a number of devices connected in parallel is given later in this book (section 101).

In a great many cases in practical work an electrician is much more concerned with the amount of resistance a thing has than what it is made of or how its internal connections are arranged.

This is true to so great an extent that it is customary to talk of "resistance" in such way as this: "Put 10 ohms into that circuit," or "Can you arrange to take 2 ohms out of the circuit," never giving a thought to the form or arrangement of apparatus which will be used to effect such result. It might be a group of lamps, as in Fig. 14 (then called a lamp bank), or a coil of wire, or a water rheostat which the person who was commissioned to effect the change might decide to use.

QUESTIONS AND PROBLEMS

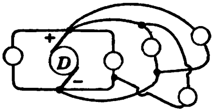
1. Which is the larger current, 325 milamp. or 3 amp.? ¼ amp. or 250 milamp.?

2. How many times as much current passes through an arc lamp as through a telegraph wire? 6 amp. flows through the lamp; the wire carries 15 milamp.

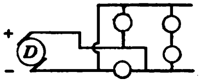
3. Classify each of the following by stating whether it is a good, fair, poor conductor, or an insulator, and why you place it as you do: (*a*) salt water; (*b*) kerosene oil; (*c*) muslin; (*d*) brass; (*e*) lye water; (*f*) blue vitriol solution; (*g*) sand; (*h*) vinegar and water; (*i*) a glove; (*j*) a shoe.

4. Using the plans shown in Fig. 1, make a diagram of a circuit containing a dynamo, three incandescent lamps, and a motor. Arrange things in as practical a way as possible.

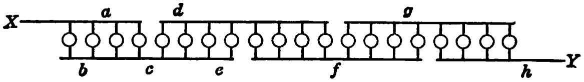
5. Redraw this diagram neatly so it is clear what sort of circuit it represents. On the new diagram draw direction of current flow.



6. In this circuit each lamp has ·1 amp. passing through it. Mark the paths of the current and the amount in every wire. Redraw the diagram in another and better form.



7. A plan for outline lighting of buildings used in an amusement park is shown by the following figure. Each lamp carries ½ amp. through it. Mark amount of current flowing and direction at *a*, *b*, *c*, *d*, *e*, *f*, etc. Current flows in at *X* and out at *Y*.



8. A No. 18 copper wire measures 0.66 ohm per 100 ft. What is the resistance of 250 ft. of it? Of 1250 ft.?

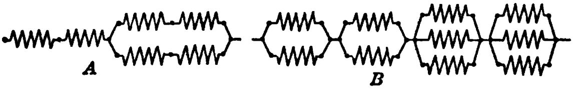
9. A No. 18 copper wire measures 0.66 ohm per 100 ft. What is the resistance of a cable 500 ft. long made of 19 of them forming a regular concentric strand?

10. A certain metal bar is ¼ in. by ¼ in. in size. 10 ft. of it measure 0.015 ohm. What would the resistance of a 10-ft. length ½ in. by ½ in. be? Of a 5 ft. length, ⅛ in. by ¼ in.?

11. No. 14 copper wire measures 2.6 ohms per 1000 ft. How much resistance has 500 ft. of iron wire of the same size? Iron has six times the resistance of copper.

12. Phoenix wire (used in electric furnaces) has a resistance 60 times that of copper. If No. 22 copper has a resistance of 16 ohms per 1000 ft., how many feet of the same size for a resistance of 20 ohms, Phoenix wire being used?

13. A certain make of cast-iron grid has 1/10 ohm resistance. Calculate the total resistance when a number are grouped as below. See *A*.



14. Calculate the total resistance when the same sort of grids as in question 13 are grouped as at *B*.

15. Each lamp in problem 7 above has 200 ohms resistance. Calculate the resistance from *X* to *Y* with all the lamps on.

CHAPTER II

ELECTROMOTIVE FORCE AND OHM'S LAW

12. Sources of Current.—In order to have a current flow there must be a source. The sources of electric current are dynamos and batteries. They have the power, when in operative condition, of driving the current through the electric circuit, forming themselves part of the circuit. That terminal of a dynamo or battery out of which current flows is called the *positive*, and that into which it returns again the *negative*, as already noted. Dynamos supply either direct or alternating current; batteries only direct current. An electric current is the same and may be used to produce the same effects in the same apparatus, no matter whether it comes from batteries or dynamos. Batteries are used for sending current through call bell circuits and some signal circuits, but in most cases dynamo current is far cheaper and is therefore made use of for lighting and power purposes. One sort of batteries, called secondary or storage batteries, often used as auxiliaries to dynamos as sources of current, is considered in Chap. XVI.

13. Electromotive Force.—Wherever we see a current of water flowing, a force is behind it making it flow. Consider any form of pump. Water is flowing from the delivery side. The actuating force may be a direct manual force, as with a hand pump; or steam pressure, with a steam pump. No matter what it is, or how caused, a watermotive force (force to move water) is there. So in an electric circuit wherever there is a flow of current there must be an electromotive force (force to move electricity). It should be understood, however, that it is not a *mechanical* force which makes current flow. If there is no electromotive force no current will flow; the direction of electromotive force determines the direction the current flows. Dynamos are only current sources because they furnish electromotive force (usually abbreviated e.m.f.). They are electric pumps, machines to drive current through circuits. It will be part of the purpose of the chapter taking up the study of dynamos to consider how they come to have an e.m.f.

14. Unit of E.m.f.—The unit of e.m.f. is the volt. Precisely similar things might be said regarding this unit, in reference to understanding its magnitude, as have been said about other units. A formal definition need not be memorized in order to understand it[1] any more than one needs to know a formal definition of a foot (measure of length) to recognize distances and make excellent use of a foot rule. E.m.f. (often called voltage) is measured by an instrument called a voltmeter. We often speak of e.m.f. separately from the machine which supplies it. Thus we speak of supplying an e.m.f. of 50 volts to a circuit without specifying just what sort of apparatus is used for this. Such an e.m.f. is called the *applied e.m.f.*

E.m.fs. in regular commercial use range all the way from 0 to 100,000 volts or more. Common values range between 100 and 600 volts in lighting and power work. Most lighting systems operate with 110 or 220 volts e.m.f. Most street railways operate with between 500 and 600 volts e.m.f. Dynamos generate 50, 110, 125, 220, 250, 500, 1000, 6600 volts, etc., on common systems. For electrochemical work they sometimes generate only 8 or 10 volts. Sometimes only a small fraction of a volt is used and a unit, the millivolt, is made use of. One thousand millivolts make a volt.

Another way to form a conception of magnitude of e.m.f. is by the physical shock received when the human body (particularly from hand to hand) is made part of an electric circuit. Few persons in good health and under ordinary conditions feel 50 volts; 100 volts give most persons an unpleasant burning sensation similar to that when we speak of a hand being "asleep;" 200 volts give a decided shock; more than 200 is dangerous, although many men do not much mind 500; 1000 volts or more is pretty sure to produce a fatal shock.

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[1] The unit of electromotive force shall be what is known as the international volt, which is the electromotive force that, steadily applied to a conductor whose resistance is one international ohm, will produce a current of an international ampere, and is *practically equivalent* to one thousand fourteen hundred and thirty-fourths of the electromotive force between the poles or electrodes of the voltaic cell known as Clark's cell, at a temperature of 15°C., and prepared in the manner described in the standard specifications.

15. E.m.fs. in Series and Parallel.—More than one e.m.f. may act to send current through a circuit. They may be connected in series or in parallel. If in series, they may be all directed the same way or against one another. Thus (Fig. 15) we may have three e.m.fs. all directed the same way. The total e.m.f. in the circuit is then the sum of the three, or 170 volts, for all being directed the same way their forces add. If all are not directed the same way, the total acting e.m.f. is obtained by adding those directed one way, making a separate sum of those directed the other way, and subtracting the smaller amount from the larger. The difference is the number of volts sending current—the acting e.m.f. The direction of flow of current is determined by the larger sum or by the acting e.m.f. Fig. 16 shows such an arrangement. 120 volts e.m.f. is directed one way and 50 volts the other way. Hence there are 120 − 50 = 70 volts to send the current. The current flows exactly as though no more e.m.f. than this (70 volts) were present. That part of the e.m.f. which would send the current the other way in the circuit from that it really takes, that which is directed against the flow of current, is called the *counter e.m.f.* or *back e.m.f.* In Fig. 16, 50 volts is the back e.m.f.

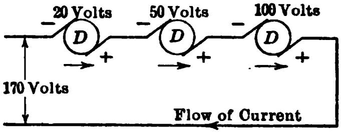


Fig. 15.

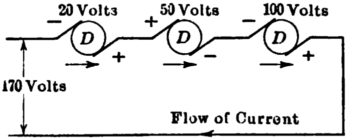


Fig. 16.

If sources of e.m.f. are connected in parallel, they must be alike or great complexities are sure to be introduced in considering the flow of current. In commercial circuits they are nearly always alike, and at this point we will limit ourselves to consideration of this case. Fig. 17 shows two dynamos connected in parallel delivering current to a circuit. Each generates 110 volts and each has current flowing through it. The current c is the sum of a_2 and b_2. After passing through the circuit current c

divides again to flow through the machines. The e.m.f. acting in a circuit like this to send the current is 110 volts, the e.m.f. of either dynamo. The presence of the second machine has not added any e.m.f.; it has simply provided a means such that the current in the main circuit has come from two sources rather than one. This is the main advantage of parallel connections. Notice that around the local path through dynamo *A* and back through *B* the e.m.f. of *A* "bucks" that of *B* and no current could flow if the circuit were open at *c*. There is a rise of voltage from a_1 to a_2 through dynamo *A* of 110 volts; likewise a rise through *B* from b_1 to b_2 of 110 volts. Hence at *X* we have a part of the circuit 110 volts higher than at *Y* and this 110 volts sends the current on around through R_1 and R_2. Therefore by putting two equal e.m.fs. in parallel we have no more volts to send current through the circuit than when one alone acts, but the current is bound to flow around as marked at *c, c, c* dividing so part passes by a_1 through dynamo *A* and the other part through b_1 and dynamo *B*. a_1 equals a_2.

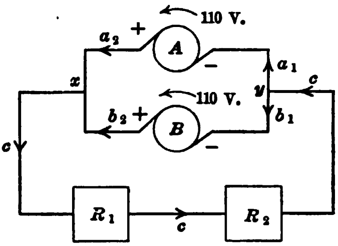


Fig. 17.

Up to this point everything which has been said applies equally well to either direct or alternating currents. The diagrams have, however, been made for direct-current apparatus. The laws regulating the flow of direct current and alternating current, and the apparatus for generating and using each kind, are sufficiently unlike so that direct-current principles and apparatus will be explained before the subject of alternating current is taken up.

16. Ohm's Law.—The amount of current which flows in a circuit is determined partly by the resistance of the circuit and partly by the amount of e.m.f. sending it. Ohm's law gives us the means of computing the amount. It may be stated thus:

The amount of current (amperes) flowing in an electric circuit can be determined by dividing the e.m.f. (volts) in the circuit by the resistance (ohms) of the circuit.

This may also be expressed in the form of a mathematical formula or equation:

$$\text{Current} = \frac{\text{e.m.f.}}{\text{resistance}}; \quad \text{amperes} = \frac{\text{volts}}{\text{ohms}}; \quad I = \frac{E}{R}.$$

In the last of these three forms the letters commonly used as abbreviations are put down. E stands for e.m.f.; R for resistance; and I is used for current, since C has been reserved for another electric unit little known in commercial usage.

Ohm's law is a most important one. It has constant usefulness in almost all practical electrical problems. It applies to any circuit and to any magnitude of I, E, or R. It is for direct current and applies after a steady flow of current has been established.

An example or two will serve to show how it is used.

1. A dynamo having a resistance of 1 ohm and an e.m.f. of 125 volts has a lamp whose resistance is 24 ohms connected across its terminals. How much current flows in the circuit?

$$I = \frac{125}{1 + 24} = 5 \text{ amp.}$$

2. Suppose a dynamo which generates 49.5 volts and the resistance of which is ½ ohm has 200 ft. of No. 16 german silver wire connected from the + to the − terminal. How many amperes will flow through the wire? (Take german silver at 20 times the resistance of copper). The wire has 16 ohms resistance and so

$$I = \frac{49.5}{16.5} = 3 \text{ amp. in the wire.}$$

By simple modification of the Ohm's law formula another class of problems is easily solved. Refer to Fig. 2 for a circuit under consideration and note the following as typical problems.

3. How much e.m.f. must a dynamo generate in order to send 10 amp. through a series circuit made up of seven arc lamps each having 5 ohms resistance, 2000 ft. of No. 7 copper wire for connections and a dynamo whose resistance is 1 ohm?

Wire	1 ohm
Dynamo	1 ohm
Lamps 7 × 5 =	35 ohms
Total resistance	37 ohms.

From $I = \frac{E}{R}$ we have $E = IR$; substituting $E = 10 \times 37 = 370$ volts.

4. A circuit made up like that of Fig. 2 has a current flowing in it of 9.6 amp. The dynamo is generating 2500 volts. What is the resistance of the circuit?

From $I = \frac{E}{R}$ we have $R = \frac{E}{I}$; hence $R = \frac{2500}{9.6} = 260.4+$ ohms.

17. Difference of Potential.—As has been explained in an earlier paragraph of this chapter, it is the e.m.f. which sends a current through a circuit. This is the force which drives the current through the resistance, and when current is flowing in a circuit this electromotive force is being spent all through the circuit. If the whole force is spent in the whole circuit, as must be clear, then some part of it is spent in each part of the circuit. If a dynamo having 100 volts e.m.f. drives the current through a whole circuit, part of it, say 25 volts, is sending the current through the resistance of some part of the circuit. An examination of such part would show 25 volts gone there—spent there. Suppose we think of the circuit shown in Fig. 18. The dynamo is generating 100 volts: 25 of these are spent in getting current through R_1, 40 in getting the same current through R_2, 30 in getting it through R_3, and 5 in getting it on through the resistance of the dynamo (we are neglecting any volts required to get current through the connecting wires). From *a* to *b* then 25 volts are spent. This is called the difference of potential between *a* and *b*; the fall of potential from *a* to *b*; the drop of potential from *a* to *b* or in the resistance R_1. The abbreviation for difference of potential is P.D. This expression has a special and definite meaning, connecting it with certain energy relations which cannot be explained here. The term e.m.f. is reserved for the generated volts, those for which the dynamo machine is operated and those due to which current flows. In fact by the e.m.f. we mean those volts which would be found present in an electric circuit which has a dynamo in operation but no current flowing because the circuit is open. The term fall of potential and the others corresponding with it are nearly always reserved for places where volts are spent. Current always flows in the

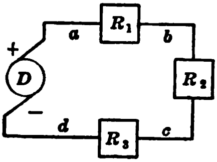


FIG. 18.

direction of the fall of potential; that means that as current is flowing, energy is being spent—is falling—as will be brought out later. Where current flows through resistance there must be a fall of potential. Where current flows through resistance of negligible amount, the fall of potential may be considered nothing.

18. Ohm's Law for Part of a Circuit.—Ohm's law is even more used in considering problems involving only part of a circuit than it is for those including the whole circuit. A statement of it for part of a circuit might be made thus:

The amount of current (amperes) flowing through any device in an electric circuit is equal to the fall of potential (volts) through the device, divided by the resistance (ohms) it has.

$$I = \frac{E}{R}$$

If, for example (Fig. 19), the fall of potential in R_1 from a to b is 15 volts and R_1 has a resistance of 3 ohms, the current flowing through R_1 and also around the circuit is 5 amp. This is certain, no matter how the rest of the circuit is made up, what amount of resistance is contained in the rheostat N, what sort of lamps are at M, or what is the e.m.f. of the dynamo.

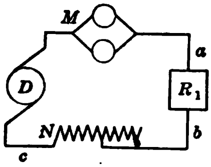


Fig. 19.

Further applications may be illustrated by examples.

1. Referring to the diagram of Fig. 18, what is the difference of potential between a and d if the dynamo is generating 130 volts, R_1 is 1 ohm, R_2 is $1\frac{1}{2}$ ohms, R_3 is $2\frac{1}{2}$ ohms and the dynamo has a resistance of $\frac{2}{10}$ ohm? 25 amp. are flowing through the circuit.

First Solution

$$E = IR$$

Fall of potential in $R_1 = 25 \times 1 = 25$ volts.
Fall of potential in $R_2 = 25 \times 1\frac{1}{2} = 37\frac{1}{2}$ volts.
Fall of potential in $R_3 = 25 \times 2\frac{1}{2} = \underline{62\frac{1}{2}}$ volts.
a to d 125 volts.

SECOND SOLUTION

$$E = IR$$

Fall of potential in the dynamo due to flow of current in its resistance = $25 \times 2/10 = 5$ volts. Of the dynamo e.m.f. 5 volts are required to drive the current through itself. Hence difference of potential between *a* and *d*

$$130 - 5 = 125 \text{ volts.}$$

One hundred and twenty-five volts is called the terminal potential difference of the machine. In common usage it passes for the dynamo e.m.f. which is really a few per cent. larger.

2. In Fig. 19 we know the fall of potential from *b* to *c* through rheostat N to be 40 volts. The current flowing in R, as already stated, is 5 amp. What is the resistance of the rheostat?

$$R = \frac{E}{I}. \qquad R = \frac{40}{5} = 8 \text{ ohms.}$$

19. Deductions from Ohm's Law.—With a constant dynamo e.m.f., varying the resistance of a circuit will vary the current flowing through it. In practice this is often accomplished by inserting a rheostat. Adjustment of the current by varying the resistance is thus made easy.

Referring to Fig. 19, if the dynamo e.m.f. were fixed in amount but the rheostat N were changed to include a different resistance, the current flowing through the circuit would change and the fall of potential in each part of the circuit would also change.

If the resistance in N be increased, the difference of potential between *a* and *b* would decrease. If the resistance in N were cut down to nothing the difference of potential between *a* and *b* would rise. If the circuit were opened at either binding post of resistance R_1 the difference of potential between *a* and *b* will at once rise to the same value as the dynamo e.m.f.

The fall of potential around every circuit is always equal to the e.m.f. applied to the circuit. No matter how the applied e.m.f. may be changed or the current in the circuit alter, this will always hold true.

The fall of potential in any resistance of a series circuit is proportional to that resistance. This must be, since the current is the same all the way around and $E = IR$. If, for example, the fall of potential in a 10-ohm coil is 2 volts, in any 15-ohm coil in the same circuit it is 3 volts.

If the fall of potential in a certain resistance which forms part of a circuit is known and also the resistance of the circuit, the applied e.m.f. can be determined thus:

Let E = E.m.f. applied to circuit whose resistance is R, the sum of R_1, R_2 and R_3.

E_1 = Fall of potential in a resistance of R_1 ohms.

I = Current flowing in the circuit.

$E = IR$, hence $I = \frac{E}{R}$.

$E_1 = IR_1$, hence $I = \frac{E_1}{R_1}$.

Things which are equal to the same thing are equal to each other

$$\therefore \frac{E}{E_1} = \frac{R}{R_1}$$

Example.—The fall of potential in a 2-ohm coil in a circuit whose total resistance is 8 ohms is 30 volts. How much e.m.f. is applied to the circuit?

First Solution	Second Solution
$\frac{E}{30} = \frac{8}{2}$	I in circ. $= \frac{30}{2} = 15$ amp.
$E = 120$ volts.	$E = 15 \times 8 = 120$ volts.

The fall of potential through parallel branches must be the same no matter what the resistance of each branch or what current is flowing in each. In Fig. 20 X and Y are parallel branches. The fall of potential from a to b is the same for each branch. The fall through X must be the same as through Y, since the two points a and b are joined by both of them.

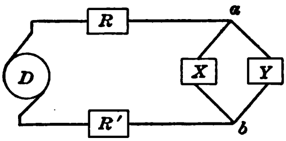


Fig. 20.

QUESTIONS AND PROBLEMS

1. Two dynamos are connected in series in a circuit. One has 110 volts and the other 80 volts e.m.f. How much total e.m.f. is acting in the circuit? (There are two answers. Give both and explain them by the aid of diagrams.)

2. I find that an e.m.f. of 375 volts is sending current through a circuit. I know there are two dynamos in series and that one is generating 500 volts. What is the other generating and how is it connected? Make a diagram.

3. Three dynamos are in series in a circuit. One generates 30 volts, one 120, and one 90. Make a diagram to show how to connect them so that the total e.m.f. acting to send current through the circuit is 240 volts; another so the total is 180 volts; another so the total is 60 volts; another so the total is no volts. Place the dynamos in the same relative positions for each case.

4. A dynamo having a resistance of 2 ohms and an e.m.f. of 240 volts has a lamp whose resistance is 48 ohms connected across its terminals. How much current flows in the circuit? How much current would flow if eight such lamps were connected in parallel to the same dynamo? How much current if three of the same lamps were connected in series and to the same dynamo?

5. Suppose I had two dynamos each generating 125 volts. How many amperes will they send through a circuit including one lamp (24 ohms, *R*), the dynamos being in series? (There are two answers.) How may the circuit be altered by adding resistance so 5 amp. flow (both dynamos are to be left connected)? Each dynamo has ½ ohm resistance.

6. A dynamo is arranged to automatically deliver 550 volts to the external circuit. How much current flows when 20 ohms are in this circuit? How much when 2 ohms are in circuit?

7. A circuit consists of a 7-ohm dynamo, 3 ohms in line wire and 30 lamps in series, each having 9 ohms resistance. If 4 amp. are flowing in the circuit how many volts e.m.f. has the dynamo?

8. Two dynamos are connected in parallel, as shown in Fig. 17. Each one has a resistance of ½ ohm. Each one generates 110 volts. R_1 is 6½ ohms and R_2 4¼ ohms. Calculate the current flowing in the circuit and through each dynamo.

9. A switchboard ammeter reads 1450 amp. The terminal P.D. of the dynamo is 116 volts. (*a*) What is the *R* through which this P.D. is sending current? (*b*) How many lamps of 232 ohms each are connected in parallel to get this resistance?

10. Three resistances of 20, 15, and 5 ohms are in series with 200 volts applied to the lot. What will the difference of potential be across each resistance? Current through each? Make a diagram and mark results on it.

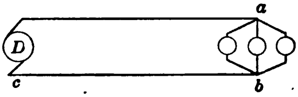
11. In a circuit made up as in Fig. 18 what is the difference of potential between *a* and *b* if the dynamo is generating 240 volts, R_1 is 4.6 ohms, R_2 is 3.2 ohms, R_3 is 4 ohms, and the dynamo has a resistance of 0.2 ohm? How much is it if R_3 is short-circuited?

12. A certain circuit is made up of a 2-ohm coil in series with a rheostat now set at 4 ohms. With 120 volts applied: (*a*) Calculate the fall of potential through the rheostat. (*b*) What would it be if the rheostat arm were moved to reduce the rheostat resistance to 2 ohms?

13. I have five devices respectively measuring 5, 10, 20, 25, and 40 ohms. A dynamo delivers 100 volts at its terminals and sends current to all these devices connected in parallel. The wires for connection have too little resistance to count. Make a diagram of the circuit and mark the amount of current in dynamo, in each device, and in each connecting wire.

14. An arc light ($R = 5$ ohms) has a current of 10 amp. flowing through it. A resistance is in series with the light, and 110 volts send current through them. How many volts fall of potential in the resistance? How many ohms in it?

15. A dynamo supplies a group of lamps connected from *a* to *b*. There are 20 of these lamps (only three shown) having 80 ohms each. Each line wire is 400 ft. of No. 7 copper wire. There is a loss of 6 volts from *b* to *c*. The dynamo has $\frac{1}{10}$ ohm resistance. Find its generated e.m.f. and the current in each lamp.



CHAPTER III

MAGNETS AND MAGNETIC FLUX

20. Magnetic Force.—A compass consists of a small magnetized piece of steel (the magnet needle) mounted on a vertical pivot, usually placed in a brass box with glass top so air currents will not influence the position taken by the needle and it will not become displaced. In Fig. 21 is shown the sort of compass which is meant. If the box is held so the needle is free to take a position of its own choosing, it will always turn and stand with one end pointing toward the north and with the axis of the needle in a *N* and *S* line. The end of the needle pointing to the north is called the *North Pole* and the other end the *South Pole*. Some force must be pulling the poles of the magnet to turn it on the pivot or to keep it pointing *N* and *S*. This is the magnetic force of the earth, which is present all over its surface.

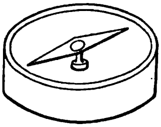


FIG. 21.

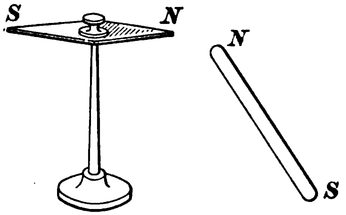


FIG. 22.

If we take a bar of steel which has been magnetized (methods of magnetizing will be described later) and approach one end to one end of the magnet needle as shown in Fig. 22, a new magnetic force is seen in operation, the force which the magnetized bar carries around with it. With the two *N* poles near each other (as in the figure) they repel each other. If unlike poles are approached they attract.

21. Magnetic Field.—The magnetic field of a magnet is the space in which it exerts magnetic force. A small compass needle placed anywhere near a bar magnet takes a definite position. If the magnet is laid on top of a table on which a sheet of paper has been placed and then the compass needle is put down at a large number of points and the direction it points recorded, we find that a picture of the field of force is developed, something like that of Fig. 23. This shows it only in one plane; the same thing holds for any plane around the magnet. In this figure the arrow point stands for the *N* pole of the magnet needle. The figure shows that the field has definite direction at every point and that the magnetic force of the field acts along lines. Indeed, since *N* poles repel *N* poles but attract *S* poles, if it were possible to have a free *N* pole and we started it off from any part of the end of the bar marked *N*, it would move along some line and stop at the *S* pole. By general agreement such lines are called lines of magnetic force, or lines of force, and they are said to have the direction along which a *N* pole would move.

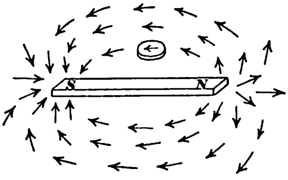


Fig. 23.

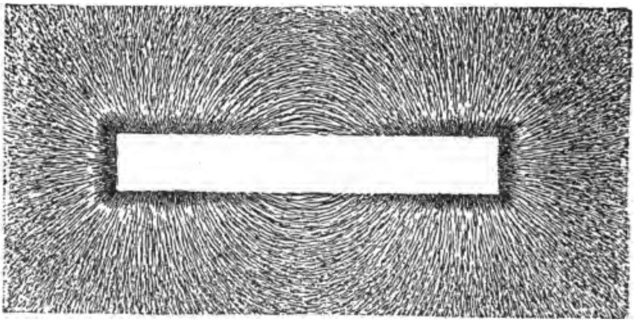


Fig. 24.

The field of force around a bar magnet can be seen more clearly perhaps by placing a sheet of paper over the bar, dusting fine iron filings and then tapping the paper gently. The result of this process will be to secure a formation like that shown in Fig. 24, for the little filings set their longer axes along the lines of force.

22. The Magnetic Effect of Current.—If a compass is brought near a wire carrying current (a couple of amperes or so) a decided effect is produced on the direction in which the needle points. Thus, suppose a wire coming directly up out of the paper, as in Fig. 25, and current flowing up through it. A plot of compass needle directions for a number of settings of the compass would show the result there given. The force must be the same kind as in other cases, and so we see that current has a magnetic field around it. Further examination would show that the magnetic force gets bigger as current increases, disappears when current stops, and reverses if current is reversed.

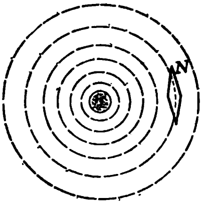


FIG. 25.

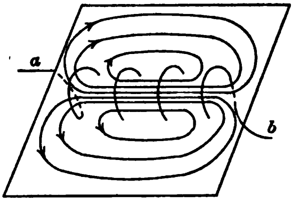


FIG. 26.

If a wire is made up into a coil, as in Fig. 26, and a current sent through it, there will be produced a magnetic field such as shown in this figure. This can be produced by the use of iron filings on a sheet of paper placed as shown. If the coil with current in it were suspended and allowed freedom of movement, it would turn and stand with its axis in a N and S line as a magnet needle would do; while, if it were used as was the bar magnet of Fig. 22, the same results would be produced. The coil is in fact the exact equivalent of a bar magnet, but by varying the current in it, its strength can be varied; while, if we explore the lines of force with a magnet needle, we find they run *through* the magnet (coil) as well as outside. It would be called an electromagnet. Common usage, however, keeps this term for a structure having magnetizing coils wound on an iron core.

23. Magnetic Flux.—The lines of magnetic force in the figures shown, or in any other case, are merely the stream lines of magnetic flux. A conception of magnetic flux may be secured by using as illustration a simple analogy.[1] Suppose we have a tube a few inches long within which is mounted a force pump which, when in operation, will draw a fluid in at one end and expel it from the other. While this pump is in operation let the tube be immersed in a tub of water all through which are sawdust particles. After steady conditions have become established, observe the liquid. The whole volume is in motion; within the tube and near its ends the liquid has high velocity, but out in the tub the motion is slow. The sawdust particles are marking out stream lines in the fluid. The stream lines are continuous in closed paths. The same stream which passes down the tube returns in much wider paths to the other end by way of the whole volume of fluid. The amount of water moving through the tube per second is the same as the amount returning to the other end outside the tube. Here is a picture of the magnetic field—a field of magnetic flux. If into the tub we insert an object such as a small block, it experiences a force to drive it along the stream lines, and the nearer the end of a tube it is placed the greater the force experienced. It is repelled from one end and attracted to the other. While this analogy fails at some points it can be much elaborated and is very useful in picturing the real facts of magnetism. There is then a magnetic flux whose stream lines we call lines of magnetic force; this flux passes through magnets and on around, completing a magnetic circuit. The same total flux is found at every part of a magnetic circuit; the same flux goes all the way around. In forms of magnetic circuit so far shown this is not so clear as in others later described. Taking the magnets of Figs. 23, 24, or 26, the return path for the flux passing through the magnets and out of the *N* pole is through all the space surrounding them.

The analogy may be used further for a partial explanation of attractive and repulsive forces between magnets. Suppose we put two tubes with their enclosed force pumps under the water. Each will have its own effect in producing currents. If certain ends are approached, the tubes, by means of these currents, repel each other. If one tube is reversed, by the same means they attract one another. If we took an instantaneous photograph of the flow of particles when both tubes are in operation we would secure a picture like Fig. 27 which is a reproduction of a magnetic field due to two magnets. The main difference arises from the fact that some flux emerges from the sides of the magnets, while all the water would emerge from the ends of the immersed tubes.

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[1] Kapp: "Dynamos, Alternators, and Transformers," page 36.

Many persons find it difficult to gain a satisfactory conception of magnetic flux because it seems so mysterious. Since it affects none of our senses, it is difficult to believe in it as a reality. And yet many examples may be cited of commonplace things which are just as mysterious. There is light flux, for example, the streaming of light out from light sources, of which we are quite unconscious unless our open eyes happen to receive it. Dust particles in the air may be used to reveal it where otherwise we would not even suspect its presence. Or there is air flux, the streaming of air which we call air currents or breezes, about the horizontal streaming of which we know something, but whose complex real flowing is only just beginning to be revealed as aviators encounter curious conditions which even a few feet before them they are unable to anticipate. Observation of motions of small and of light objects

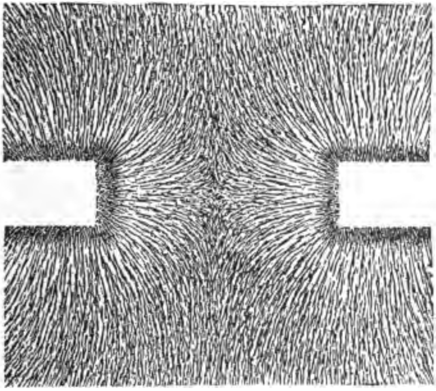

Fig. 27.

reveal air currents of which we would be absolutely unconscious without them.

24. Direction of Magnetic Flux.—The direction of magnetic flux is such that it always passes out of *N* poles and into *S* poles. The amount of magnetic flux shows the strength of the magnet. If twice as much flux comes from the *N* pole of one magnet as from that of another, the second magnet is twice as strong as the other. There is a fixed relation between the direction of flux and the direction of current flow. Compare Fig. 28 and Fig. 25. A useful rule for connecting direction of current and direction of flux is the following:

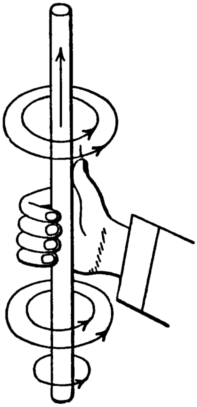

Fig. 28.

Grasp the conductor carrying the current in the right hand with the thumb pointing along the conductor in the direction the current is flowing; the fingers will point in the direction the flux is going.

This rule is easily extended to include every case where it is desirable to know this relation. In Fig. 26, for example, in order to produce flux in the direction there shown current must enter at *a* and pass out at *b*.

25. Magnetization of Iron.—Iron has the peculiar property that it is a better conductor for magnetic flux than other materials, and on this account is said to have more permeability. This quality of iron is shared to a slight degree by the metals nickel and cobalt. All other materials are equally good conductors for magnetic flux and are therefore said to have the same permeability. Their permeability is 1, the same as air. Wrought iron and cast (machinery) steel have about the same permeability, cast iron about half as much. The permeability of soft wrought iron may easily be 1200 or 1500. This means that with a very simple magnetic circuit like that of Fig. 29, if we

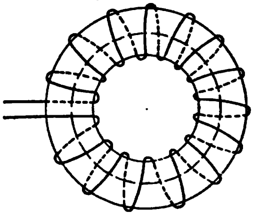

Fig. 29.

substitute wrought iron for the wooden ring on which the coil of wire was first wound, with the same current flowing in the same coil, 1200 or 1500 times as much flux would pass around the magnetic circuit. The flux path for either case is indicated by a dotted line.

26. Flux Intensity and Saturation.—In many problems it is important to be able to express the amount of flux as a numerical quantity. There is a unit for expressing amount of flux called the maxwell; but instead of speaking of 2,000,000 maxwells, it is much more common to say 2,000,000 lines of force, referring to the lines already explained. If the total flux be divided by the cross-section of the magnetic circuit in square centimeters[1] the flux per square centimeter is determined, which is called the *flux intensity,* or lines per square centimeter. This quantity is important because iron has a peculiar variation in its permeability such that when magnetized to a high flux intensity the permeability greatly diminishes. Under such conditions it is said to be getting *saturated,* and with very high flux intensity, to be saturated. Saturation is used to express the idea that the iron has reached a condition such that it has received through it all the flux which it can receive as a material having better permeability than air. Saturation is a rather indefinite term. With good wrought iron and steel it would be reached at something like 20,000 or more lines per square centimeter, while in cast iron it would be reached at 8000.

27. Ampere-turns.—In the case of all electromagnets, current flows through turns of winding to send the flux through the magnetic circuit. Current in turns is the cause of the flux.

Experiment, as well as the mathematical theory of the subject, shows that the amount of flux in a given magnetic circuit depends upon and is regulated equally by the current in use and the number of turns through which the current flows. Hence, given a magnetic circuit (as, for example, Fig. 29) it makes no difference whether we use 20 turns of winding with 3 amp. in them, or 60 turns and 1 amp., or 600 turns and $\frac{1}{10}$ amp., the flux would be the same. The product of the amperes by the turns—the *ampere-*

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[1] A centimeter is a measure of length in a system of measurement much used in scientific work. One inch is 2.54 cm. long. A square inch contains 6.45 sq. cm.

turns—is the same for each of the above windings. It is a general principle then that a certain number of ampere-turns produce a certain amount of flux in a magnetic circuit no matter how made up.

Increasing ampere-turns results in increasing the flux. If the path for flux has iron in it and the iron is not saturated or approaching saturation, the flux would increase in the same proportion as the ampere-turns. But if saturation is being approached, the increase in flux will not be as much as in proportion, and the more highly saturated the iron the less the increase in flux for a given increase in ampere-turns.

28. Compound Magnetic Circuits.—Practical magnetic circuits are usually compound—that is, made up of more than one material. They are generally of iron or nearly all of iron, and so the flux path is marked out in a very clear way. Such circuits are called closed magnetic circuits. Examples of these are given in Fig. 30.

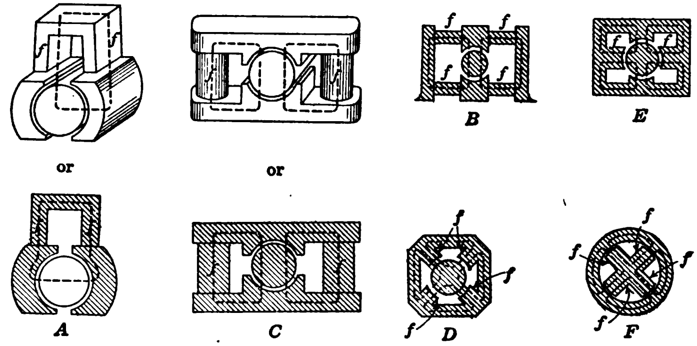

Fig. 30.

The iron parts are shaded; the flux paths are indicated by a single dotted line for each path; the usual location of magnetizing coils is indicated by the letter *f*. In each case there is a closed magnetic circuit, all of iron except a short air gap. The more completely the path for magnetic flux is all of iron the more magnetic flux there is sure to be for the ampere-turns in use.

A is a single horseshoe magnet form. *B* and *C* are double horseshoe magnet forms, while *D*, *E*, and *F* are multipolar forms. *D* and *F* are forms which can be easily modified to have any even number of poles.

Taking the single horseshoe form as a simple example for further consideration, note (Fig. 31) that the different parts might be of different materials, of different shapes, and of different sections. *y* would be called the yoke. It might be of wrought iron, rectangular in section and quite massive. *f f* are the field cores or the cores. They are likely to be of wrought iron, circular in section. *pp* are the poles and they might be cast iron. *a* is the cylindrical armature placed concentric with the bore of the pole faces, and separated from them by a short air gap through which the flux passes. The armature is made of sheet-steel discs. In a normal magnetic circuit the flux density might be 8000 lines per square centimeter in the armature core, 9000 in the air gap, 16,000 in the field cores, and 6000 in the yoke. The total flux through the magnetic circuit, the same all the way around, might be anything from a half million lines up to several million, depending on the size of the structure. The ampere-turns placed on a dynamo magnetic circuit to magnetize it are likely to be somewhere from 5000 to 10,000.

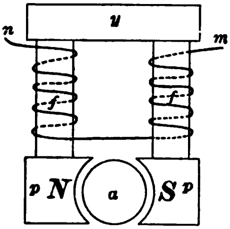

Fig. 31.

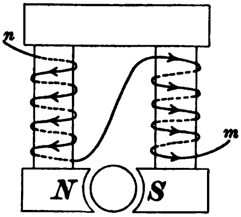

Fig. 32.

All the flux does not keep in the iron path—the useful path; for in a dynamo machine, as will later appear, the windings are put on the magnet cores for the purpose of getting flux through the armature. Since there is no insulator for flux, some instead of crossing the air gap into the armature passes across a longer air gap from pole to pole, or even field core to field core, without reaching the armature at all. This is called leakage flux. Multipolar forms generally have less leakage flux than single horseshoe or bipolar forms.

In order to produce *N* and *S* poles as marked in Fig. 31, that is to have flux cross the armature from left or right, current must flow in at *m* and out at *n*. However, the windings may be put on differently. See Fig. 32 for one other way, in which case current flows in at *n* and out at *m*, and the same direction of flux holds as in Fig. 31. The reader should make sure that by the use of the rule for the relation of direction of current and direction of flux, as stated in section 24, he sees clearly that the magnetizing effect of the coils in Figs. 31 and 32 produce the flux, sending it in the direction state. In using the rule, sink the fingers into the iron and point them along the known flux path. If this is clear, it will be easy to arrange windings for any of the other multipolar forms shown.

If the current flowing in the winding of the magnetic circuit represented in Figs. 31 or 32 should be increased in regular amounts, as for example, 10 per cent. at a time, the flux is not likely to increase 10 per cent.; for some part of the magnetic circuit (in this case most likely the field cores) will be approaching saturation. The bigger the current the more nearly has the whole circuit approached saturation. Hence a time will be reached when increasing current would increase flux by a comparatively unimportant amount.

29. Results of Magnetizing.—When the current flowing in the magnetizing ampere-turns on a closed magnetic circuit is interrupted, the flux does not entirely disappear. That which is left is known as residual magnetism. In some apparatus, residual magnetism is an advantage and in some a disadvantage. In dynamo machinery some residual magnetism is desirable. The property iron has which leads to its retaining magnetism is called *hysteresis*. Iron always tends toward the former condition of magnetization it had. It has a magnetic memory. If a magnetic circuit had not been magnetized before, and 6000 ampere-turns are applied, a flux of a million lines may be produced. When the current is cut off, instead of the flux dropping to nothing, perhaps 50,000 lines are left. In the same way if it has been magnetized by an increase of ampere-turns from 6000 to 7000 and this has produced 10 per cent. increase in flux, a decrease to 5000 again will cause a decrease *less than* 10 *per cent.* This is said to be the effect of hysteresis.

If current in a magnetizing circuit be repeatedly made and broken, the flux comes and goes with the current up to as high a rate of opening and closing the circuit as can be desired; while if the current were reversed and re-reversed, the flux would vary with the current both in direction and magnitude, except for hysteresis effects, as already explained.

It happens that we know something of the reason why iron is a better conductor for flux than other materials, and this is an aid in explaining saturation, hysteresis, and other phenomena relating to its magnetization. Every molecule[1] of iron is a permanent magnet with its own *N* and *S* poles. When a piece of iron shows no evidence of magnetization, its molecules are under the influence of each other's magnetic forces, and because of their haphazard arrangement, no external magnetic force shows. When ampere-turns are applied, or the piece is made part of a magnetic circuit through which flux is sent, the molecules are brought somewhat into alignment with the force. The more the magnetizing force the closer the alignment, until when the molecules are all aligned with the force, the iron is said to be saturated. Having secured an alignment of the molecules by magnetizing, the removal of the current in the magnetizing coils leaves them to some extent in altered positions; hence the residual magnetism, and the hysteresis effects. If current is reversed, the molecules of the iron must be reversed and re-reversed with it. This causes some sort of internal molecular magnetic friction, and the iron warms up if the reversals are repeated rapidly enough.

30. Methods of Magnetizing.—The magnetizing of a magnet or magnetic circuit by the use of ampere-turns has already been explained.

Methods of making permanent magnets, in which the flux stays constant without any ampere-turns to maintain it, may be briefly mentioned. Since the molecules have a great deal to do with magnetization it will be plain that for a permanent magnet a hardened tool steel will be the thing to use. The bar is made glass hard and then the temper drawn to straw-tint at the ends, fading to blue along the bar. It is then set into and made part of such a magnetic circuit as shown in Fig. 33, where *B* is the bar and *G* the magnetizing coil.

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[1] A molecule is the smallest quantity of a substance which can exist as such.

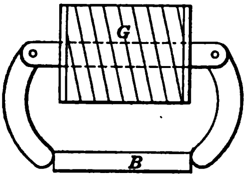


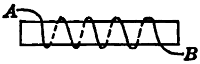
Fig. 33.

Less satisfactory ways of applying a magnetizing force are to stroke the bar with another permanent magnet or insert it in a coil like that of Fig. 26.

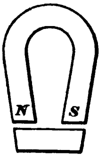
Steel of any form can be magnetized to have poles produced at any points. Iron and steel permanent magnets have the magnetism jolted out of them by mechanical vibration.

QUESTIONS AND PROBLEMS

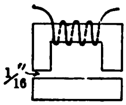
1. Current flows in at *A* and out at *B*. The coil is wound on an iron core. Mark by lines which way the flux goes. Mark the *N* pole. Draw in and around the core some lines to show the paths of the magnetic flux.



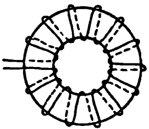
2. For a horseshoe magnet and armature as shown, show how the turns of winding are to be placed (one coil on each leg) and the direction of current to produce poles as marked. The coils are to be connected in series. Draw also some lines to show the flux paths.



3. For this magnet tell as many ways as you can by which more flux can be made to go through the magnetic circuit. Change in arrangement or material is allowed. The U-shaped magnet and armature are of cast iron.



4. The figure shows a wooden ring with a coil of wire on it. If current is passed through the coil, which way will the flux go? If the ring were changed to brass and the current were the same, how would the flux compare with that in a wooden ring? If it were wrought iron, how would it compare?

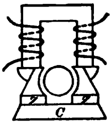


5. The flux in an iron magnetic circuit is 720,000. It has a cross-section of 12 sq. in. Suppose now the current in the magnetizing coil is doubled, how will the flux be changed? How if the current is doubled again? Explain in both cases.

6. A certain magnet has been wound with 295 turns of wire through which 4 amp. have been flowing. (*a*) A new winding of finer wire is put on. It contains 2360 turns and ½ amp. is sent through. Compare the strength of the two magnets. (*b*) Suppose with the last winding the current were increased to 1 amp. How would the strength compare with the former value?

7. Put a field winding on a magnetic circuit like that of *B*, Fig. 30, using all four horizontal portions marked *f* for the windings. Connect all coils in series and produce a *N* pole above the armature.

8. In the figure *z* are zinc spacing blocks and *c* is a cast-iron base. Mark some probable paths for leakage flux. Suggest some way to reduce its amount.



CHAPTER IV

DIRECT-CURRENT DYNAMO, E. M. F.

31. Generation of E.m.f.—Whenever a conductor cuts flux by either a movement of flux or conductor, or when flux varies through a turn of wire, an e.m.f. is generated in the conductor while the cutting or change is in progress. The amount of e.m.f. generated is proportional to the rate at which the flux cuts the conductor, or the rate at which it varies through the turn of wire. By rate of cutting flux is meant the flux out per second; although any rate may last only a very small fraction of a second.

The rate of cutting flux in a given case is determined by:

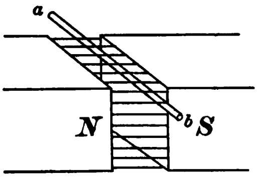


FIG. 34.

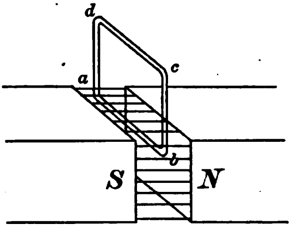


FIG. 35.

(*a*) The speed at which the conductor moves; (*b*) the amount of flux through which the conductor is cutting.

Thus, for example, in Fig. 34 is a straight conductor placed in the magnetic field found in an air gap of a magnetic circuit. If it is moved, then *while moving* an e.m.f. will be generated along it, unless the motion be in the direction of its length, for it will be cutting flux. Suppose the field intensity to be 4000 lines per square centimeter and the conductor to be moving downward through the position shown at a speed of 25 ft. per second, some number of volts will be generated. If the speed were doubled the generated e.m.f. would be doubled, or if the intensity were increased to 8000 the e.m.f. would be doubled. If both were doubled the e.m.f. generated would be quadrupled. If the intensity of flux is constant all across the pole face and the conductor keeps moving at a constant speed, the e.m.f. generated would be constant until the conductor passes out of the field; when, flux cutting having ceased, the e.m.f. drops to nothing. If the conductor increases in speed as it moves down, or the flux intensity is greater toward the lower edge, or both, the e.m.f. will increase as the conductor moves downward, until the edge of the field is reached.

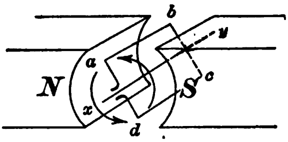


Fig. 36.

Precisely similar considerations apply to a turn of wire, as shown in Fig. 35. If moving downward in its edgewise position, it has flux through it increasing. Hence e.m.f. is being generated in it. Or, if moving upward, flux through it is decreasing and so e.m.f. is being generated.

In Fig. 36 is shown a conductor in rectangular form revolving in direction shown about the axis *xy*. Side *ab* is cutting flux and so is *cd*. Hence there must be e.m.f. generated; or from another point of view, the flux through the loop as it turns is diminishing and so there is an e.m.f. there.

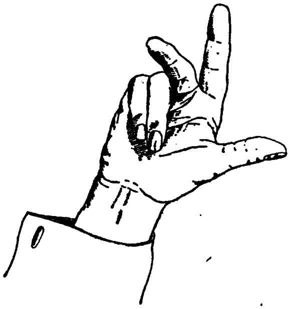


Fig. 37.

32. Direction of Generated E.m.f.—The direction of the generated e.m.f. is determined by the direction in which flux is cut. Some rule connecting direction of flux, of motion, and of generated e.m.f. must be remembered in order to be able to predict from the motion of the conductors, the direction of the e.m.f. The following is recommended:

Put the thumb and the first two fingers of the right hand all at right angles to each other (*see Fig.* 37). *If the thumb points in the direction of motion, and the first finger in the direction of flux. the second finger will point in the direction of generated e.m.f.*

This rule applies to any case of cutting flux, when the conductor considered and not the magnetic field, is moving. In dynamo machinery it applies no matter whether the machine is for direct or alternating e.m.f. Applying it to the case in Fig. 34, the e.m.f. generated by downward motion of the conductor is from *a* to *b*. In Fig. 35 by downward motion of the loop an e.m.f. generated in the side *ab* acts around the loop *badc*. In Fig. 36, *ab* is cutting flux so as to generate e.m.f. from *b* to *a* and *cd* is cutting flux to generate e.m.f. from *d* to *c*. No e.m.f. is generated in *bc* or *da*.

33. Dynamo Armatures.—In section 28 it has been noted that a dynamo armature is part of a dynamo magnetic circuit, has cylindrical form, and is built of sheet-steel discs. Strictly speaking, this is the *armature core*. It is the structure on which wires are placed so that when revolved the wires generate the e.m.f. of the machine. In Fig. 38 two forms of armature core are shown. The upper one is built up of discs like *A* about 0.02 in. thick, each one having a thin coating of japan varnish on one side to insulate it from its neighbor. They are laid up together, compressed between cast-iron end plates *cc*, and the whole thing solidly secured to the shaft *ss* by which it is supported in bearings and rotated. The lower one is built of discs shaped like *B*, with a large opening in the center. Often the discs are not only insulated by japan but they have a thin tissue paper sheet, inserted above every fifth disc. These discs are supported on a spider (*sp* in figure) which is a casting made of a hub with radial

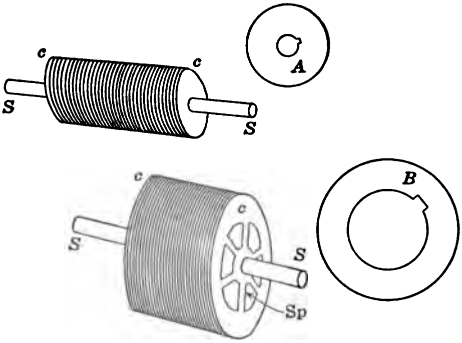


Fig. 38.

arms. End rings of considerable thickness are arranged to compress the discs and to hold them so as to make one solid structure mounted on the spider, which is keyed to the shaft.

On the outside of the cylindrical core, wires are wrapped in coils and arranged for the generation of e.m.f., these coils being held in position by fiber pins or strips usually set into sawed slots in the end discs. This constitutes the armature winding.

34. Armature Construction.—There are two sorts of armature winding in general use, ring armature winding and drum armature winding. Ring armature windings are very little used in modern armatures, but will be described first, because they are easier to explain and understand.

In Fig. 39 is an outline diagram of a ring armature. In order to make the construction clear the top part is shown in perspective in Fig. 39*A*. Two turns per coil are shown in the diagram and only one per coil in the perspective drawing. The poles of a bipolar magnetic circuit form are shown. Magnetic flux passes from the *N* pole across the air gap into the core, and then, following the route as shown in Fig. 40 enters the *S* pole. No flux crosses the central opening of the ring; and in order to make it certain that none will do so, the spider which supports the ring-shaped stampings must be of gun metal or some non-magnetic material.

In a well-designed machine the flux passes across the gap with practically uniform intensity over most of the pole face. Near the pole tips it fringes off, diminishing in intensity as they are passed, but still some comes over to the armature except for a short distance *a* as marked in Fig. 40. The width of this space in which flux neither enters nor leaves the core is determined by the spread of the poles, the distance from the tip of one pole to the next, and the length of the air gap itself.

A cylindrical structure is represented diagrammatically around the shaft in Fig. 39, several of the bars of which are numbered. This is the *commutator*. In Fig. 41 is shown a commutator as it is built, one-quarter having been cut away to show the construction. A large number of copper bars, each separated from its neighbors by mica insulation, are so assembled that their outer surfaces form a perfect cylinder. These bars are locked in place by clamping rings, shown in section in the figure. Between the bars and these rings, insulating them from each other, are mica cones, which in the upper part of the figure are shown by heavy black lines. A tubular mica piece is placed inside the bars. The two cast-iron clamping rings are driven together over

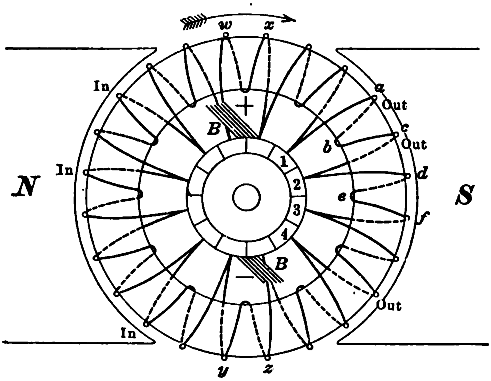


Fig. 39.

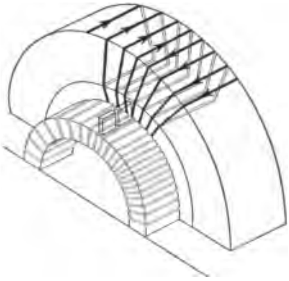


Fig. 39*A*.

the commutator bars by hydraulic pressure and then held by screw bolts, some of which show in the figure. One of the clamping rings forms a support for the other and also a barrel which slips over the armature shaft or a projecting casting made in one with the armature spider. At the left end of each bar is a milled cut into which the ends of the armature windings are soldered. In Fig. 39 the commutator shown has only 12 bars.

The armature winding is put on in the following way: Starting from a bar, as number 1, a wire is carried up over the front of the ring to *a*, then straight back along the cylinder, down on the back and around through the inside completing a turn; up around to *c* and around coming down to bar 2. From bar 2 another coil is put on, going to *d*, *e*, *f*, to 3, and so from bar to bar continuously to the point of starting. Starting from any point in the winding and selecting a direction to go there will be one continuous conducting path back to the point of starting. In following this every wire of the winding would be passed through, and each bar of the commutator be touched. Since all the wire is insulated, and the bars are all completely insulated from each other, it is not possible to find a divided circuit anywhere. A very small armature might be made with no more than 12 bars in the commutator and 12 coils in the winding. In this case each coil might have 50 turns or more in it. In larger machines with 2 magnet poles, there might be 40 or 50 commutator bars and the same number of coils, each coil having 6 turns or so, laid in two or more layers. In a big machine there might be only 1 turn per coil. In every case the winding completely covers the core, placed in one, two, or more layers; and the winding is carefully insulated from the core by paper or cloth wrappings.

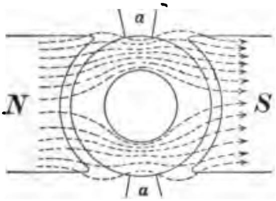


FIG. 40.

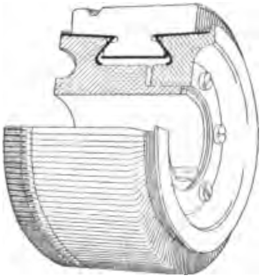


FIG. 41.

The winding might have been started just as well by passing from bar 1 through the central opening up on the back and along the cylinder to the front, or instead of starting with bar 1 and proceeding toward bars 2, 3, etc., the winding might have been started from bar 1 and wound toward 12, etc. It is only necessary that every coil be wound like every other.

The wire for such windings is magnet wire. This is copper wire on which for insulation is wound a layer of cotton threads in a spiral to make a continuous covering about 0.003 in. thick for the smaller wire sizes. A second and even a third such layer is put on when the wire is to be used for armature windings. Magnet wire is therefore either single, double, or triple cotton-covered. Armature cores are insulated by paper or fabric insulation before the wire is placed on them, and coil ends are reinforced by additional insulation where wires cross or where they are exposed to possible mechanical injury. By the use of varnish or compound the cotton and fabric insulations are reinforced and protected against moisture. Moist fabrics are "poor conductors."

35. E.m.f. in Ring Armature Winding.—If now the armature with winding on it is rotated, every outside wire will be cutting flux, and so will have an e.m.f. generated in it. If the rotation is as indicated in Fig. 39, the e.m.f. in every wire on the right side of the armature at the instant under consideration will be directed out toward the observer, and in every wire on the left side it will be directed in (Rule of section 32). Only these wires on the outside of the cylinder have any e.m.f. in them.[1]

Following the winding all the way through and bearing in mind the direction of e.m.f. wherever encountered, we will find that along the right-hand side all the individual e.m.fs. in the wires are connected in series; the same is true for those on the left-hand side, but the e.m.f. of the left side is directed against that of the right-hand side. The number of volts generated in each wire will be the same except at and just beyond the pole tips. There it diminishes, for, while the speed of cutting of each wire is the same, the intensity of flux is less near and beyond the pole tips, as already explained. For the sake of simplicity assume that 2 volts is generated in each wire except those lettered *w*, *x*, *y*, *z*, which would not have any e.m.f. in them. Then on the right-hand side are 10 conductors in series each generating 2 volts, or 20 volts in all, directed toward the upper part of the winding. On the left-hand side the same number of conductors in series generate 20 volts, also directed toward the upper part. Hence between the upper part of the armature and the lower is a difference of potential of 20 volts derived from two e.m.fs. in parallel.

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[1] It will be well at this point to notice that the e.m.f. induced in each turn may be considered as due to the flux through the turns changing as much as on account of wires cutting flux. A turn at either top or bottom of the core has as much flux as possible through it, but no change in flux is experienced for some little distance it moves. As turns move downward in the upper right-hand quarter, flux through them is diminishing and so e.m.f. is generated.

In order to be used, this e.m.f. developed in the rotating armature must be available between fixed terminals. It is the purpose of the commutator to make this possible. By allowing a pair of stationary brushes to rub on the commutator, placing them as shown in Fig. 39, the difference of potential of 20 volts is constantly available between these fixed points no matter what part of the armature winding is uppermost at the time.

Every coil in the armature winding must have the same number of turns and all be wound the same way. Suppose 22 volts were generated in one side and 20 volts in the other; then locally through the armature winding there would be an e.m.f. of 2 volts sending current through the resistance of the wire on the armature which is always small.

If the direction of rotation of the armature or the direction of magnetic flux through the magnetic circuit were reversed, the e.m.f., and so the current sent out through the brushes, would be reversed.

Multipolar ring armature windings can easily be made, but they are so rare that no space will be taken to describe them.

36. Function of Commutator and Brushes.—The *commutator* gives the means of constantly keeping hold of those parts of the armature winding between which the generated e.m.f. of the machine is produced while the armature is in rotation.

The *brushes*, by rubbing on the commutator (see *BB* of Fig. 39), form an important part of the path by which the current flows out of the armature into the external circuit and back again from it to the winding. In modern practice they are almost always of carbon (sometimes of graphite) and are pressed to the commutator by springs so a good contact is always maintained. In Figs. 42 and 43 are shown two forms of brush holders. It is always best to have at least two brushes at each point where they are applied to the commutator for the sake of more perfect contact. In Fig. 42 there are six brush holders mounted together on a brush-holder stud. In Fig. 43, a brush is in place in the holder, with a flexible wire connector (called a pig-tail) from it to a fixed part. This is used to prevent current passing through the springs or through imperfect contacts on the way to the machine terminals.

That brush is positive at which current flows out of the armature. In Fig. 39 it is the upper brush as marked. In a machine which is delivering 50 amp., half of this flows through each side of the winding, 25 amp. from each side uniting and flowing out through the positive brush and on to the circuit.

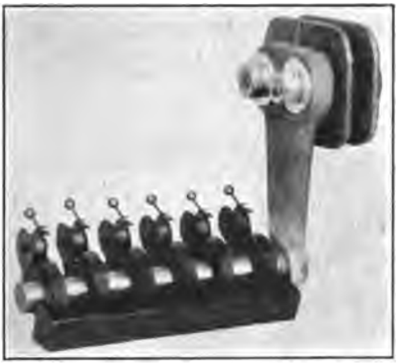

Fig. 42.

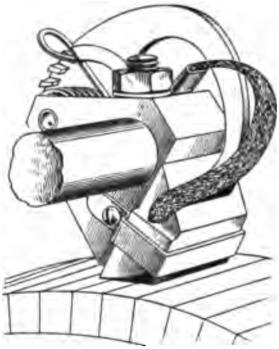

Fig. 43.

The proper place for the brushes has been indicated. This is on a perpendicular line where no e.m.f. is generated. This line through the armature, perpendicular to the direction of the flux, is the *neutral line*. Here the brushes short-circuit coils in which no e.m.f. is generated. If they were moved around the commutator, less e.m.f. would be available between them, and they would be short-circuiting coils in which e.m.f. is generated. In the very low resistance of these coils large current would flow, and so sparking at the brushes occur. Brushes must always operate sparklessly, for wherever there is sparking heat is generated, commutator bars are cut away, and brushes are pitted out. The commutator and brushes are parts of a machine which are too expensive to permit rapid deterioration of them.

There is another important function of the brushes. In Fig. 44 is shown part of the armature under discussion. If current is being taken from the machine it flows as here indicated. Coil *A* has the current of one side of the winding flowing in it (say 10 amp.), and coil *C* the current of the other side, both currents flowing to unite at the brush. Now with the armature rotating, let coil *A* move over to position *B*. As the short-circuit by the brush closes, *B* has 10 amp. in it, while as soon as it passes over to position *C* it must have 10 amp. flowing in it in the opposite direction. In this small motion of the armature the current in this coil would have to change by 20 amp. Here is a coil wrapped on an iron core with current in it. Current always produces magnetic flux and so this current sets up flux in the iron. When the current changes, flux changes too, and this will produce an e.m.f. in the coil which is short-circuited in a direction to make the current persist. Sparking results as *B* passes to position *C*, unless some means is taken to reduce and reverse the current in *B* and have it flow right when the short-circuit is opened. It is mainly for this reason that carbon brushes are used in order to insert in the short-circuit the high resistance which such a brush has. Carbon brushes also wear very well on a copper commutator.

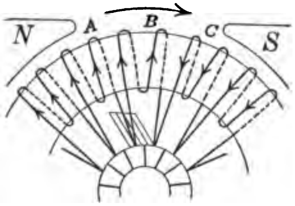

Fig. 44.

37. Armature Reaction.—When current is flowing through an armature it magnetizes the core—sends flux through it. In Fig. 45 the direction of current corresponding to former diagrams has been marked. It will be clear that, due to this armature current, flux passes down both sides of the core, making the top a *S* pole and the bottom a *N* pole. When the magnetizing force of this current and of the field coils operate at once, the combination causes the resulting flux to be skewed around in the direction of rotation of the armature. Hence the flux is crowded into pole tips *A* and *C*, and reduced at tips *B* and *D*. This may be better understood by thinking of an analogy in section 23 of Chap. III. Imagine a vessel of water shaped like the ring armature core below. Water is streaming in at the left side and out at the right. Another current is now started which flows in at the top and out at the bottom. Think how the stream lines of water flux would be altered by its presence. Thus the neutral line comes to be shifted through a small angle and makes it necessary to shift the brushes a little to keep them at the non-sparking point. This whole phenomenon is known as armature reaction. In most modern machines the design is such that there are not many armature ampere-turns compared with those in the field winding, and so there is not much armature reaction even with large current flowing through the armature windings. A good modern machine with carbon brushes will operate without sparking and without readjustment of the brushes from no current delivered by the armature up to the largest for which the machine is designed. The amount of armature reaction will of course vary with the amount of current flowing in the armature.

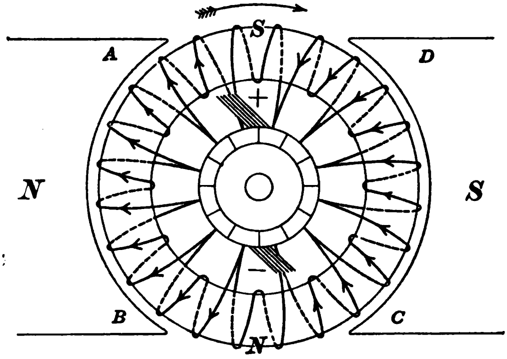

FIG. 45.

38. Eddy Currents.—Currents which circulate through a block of metal in such a way that it is impossible to define the exact path they take or to use an ammeter to tell the amount of current flowing are called eddy currents. A simple example might be found if we consider the case of a rectangular plate of metal taking the place of the conductor shown in Fig. 35. Such a rectangular plate would (in position shown) have an e.m.f. generated in its lower edge but none in its upper edge. Current will therefore flow in a rather indefinite path away from the observer in the lower part of the plate and toward him in the upper part to complete the circuit.

In a dynamo armature core eddy currents are set up (see Fig. 46). Along the outer edge of the cylinder as much e.m.f. is generated per inch of length as in the wires of the winding. Further in, the e.m.f. is less since the iron there is moving less feet per second, and on the inner edge there is no e.m.f. Hence eddy currents would flow as shown in the figure. It is for the purpose of eliminating these currents that the armature core is built of thin iron plates (has a laminated core) which are insulated from each other. If the thickness of a disc is halved, the e.m.fs. generated are cut in two and the resistance of the path for the current increased; in fact, it can be proved that for thin discs halving the thickness cuts down the eddy-current loss to quarter its former amount.

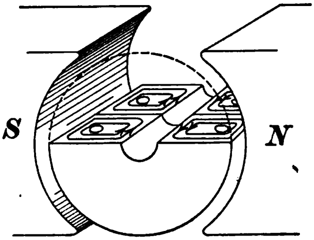

Fig. 46.

39. Amount of E.m.f. Generated.—The e.m.f. which an armature generates is determined by the rate at which the wires cut flux; that is, the flux cut per second. If a wire cuts flux at the rate of 100,000,000 lines per second, 1 volt is generated. As a wire moves through a magnetic field the rate of cutting flux might vary for every position the wire took, and so its e.m.f. be very variable. In the case of an armature like that which has been described the e.m.f. in a given conductor changes as the armature revolves. If there are not many conductors, or if the number of commutator bars are few so that as the machine runs there may be different numbers of conductors generating e.m.f. for different positions of the armature or a varying resistance from brush to brush, a pulsating e.m.f. may be secured. In practical cases the pulsation is very slight indeed.

If Φ[1] is the amount of flux through the magnetic circuit of a two-pole dynamo, any wire cuts this twice in a complete revolution of the armature. If the armature makes n revolutions *per second* the flux cut in a second by a conductor is $2\Phi n$. Hence the average e.m.f. generated in one conductor in volts is

$$E = \frac{2\Phi n}{100{,}000{,}000}$$

If the armature has on it c conductors which cut flux, $c/2$ of these in series produce the whole e.m.f. of the machine. Hence the e.m.f. of the machine would be

$$\text{E.m.f. of two-pole dynamo} = \frac{2\Phi n}{100{,}000{,}000} \times \frac{c}{2}\,.$$
$$= \frac{\Phi cn}{100{,}000{,}000}$$

for no matter in what position the armature stands there are conductors generating every possible value of e.m.f., and so the average e.m.f. of one multiplied by the number in series gives the steady e.m.f. of the machine.

This formula enables one to solve many practical problems and is equally valuable to show that increasing flux, or turns of winding or speed of machine are all of equal weight in increasing the e.m.f. of a dynamo.

Probable magnitudes for Φ and c have been already given; n is rarely over 30 even in a small machine.

40. Dynamo Field Excitation.—Advantage is taken of the residual magnetism in dynamo magnetic circuits to make them *self-exciting;* that is, to supply the current which, flowing in the turns of their own field windings, supplies the magnetic flux of the machines.

There are three types of dynamos distinguished by the connections of field windings—shunt, series, compound. These are shown in Fig. 47 diagrammatically. Any one of them may be used on any of the magnetic circuits shown in Fig. 30 or on any other forms. Should the end of the shunt field winding on the compound-wound field shown connected at *a* be removed and connected at *b*, the machine would be called a compound dynamo with long-shunt field connection. As shown it is a compound dynamo with short-shunt field. In practice a field rheostat is always included in the circuit of the shunt field. By means of this the current in the shunt field can be regulated, the flux in the magnetic circuit changed, and so a control of the dynamo e.m.f. be secured. Fig. 48 shows more fully than the diagrams the arrangement of field connections. It shows a shunt dynamo equipped with field rheostat.

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[1] A letter of the Greek alphabet, pronounced "fee."

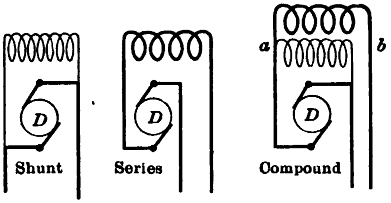


FIG. 47.

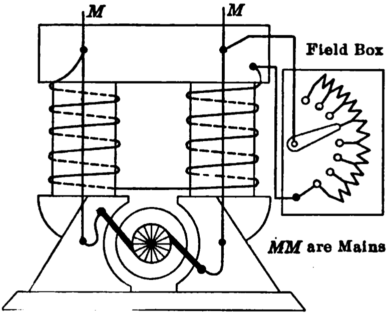


FIG. 48.

A shunt field winding has comparatively little current through it and this flows through a very great many turns of wire. A series field winding has a few turns of large wire, but the whole dynamo current goes through it. A compound field winding has both shunt and series windings on it, each with its distinctive construction. Current is made to flow in them in such direction that the ampere-turns of both windings assist each other in producing flux.

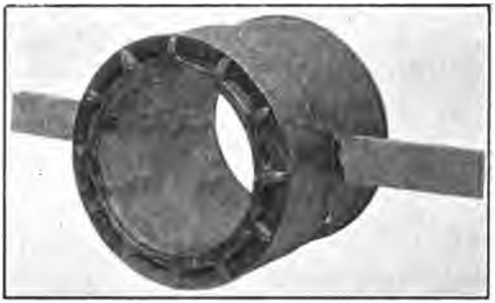


Fig. 49.

The field coils are sometimes wound on spools and sometimes are simple-formed coils held in form by wrapping of tape. Figs. 49 and 50 show field coils of each of these kinds. The heavy strip shows the terminals of the series winding; the fine wire or binding post connection shows the shunt field terminals. Each of these field coils shown must be for a compound dynamo since it has both shunt and series coils in it. It is common practice to put a coil of series winding at every point on a magnetic circuit where a shunt winding is placed.

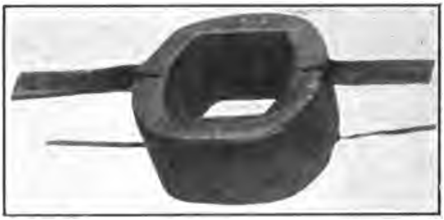
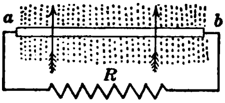


Fig. 50.

The wire for shunt field coils is copper magnet wire insulated with cotton (see section 34), often single cotton-covered. The series winding is often of strap copper and may be also insulated the same way.

QUESTIONS AND PROBLEMS

1. Here is a uniform magnetic field. The dots represent the ends of lines showing that the magnetic flux comes straight up out of the paper. *ab* is a conductor which is moving in the direction shown by the arrows. Its ends are kept connected through a resistance *R*. In what direction is the generated e.m.f.? Will current flow in the circuit? Which way? Would a voltmeter connected from *a* to *b* show a reading? When the moving wire has passed beyond the field so that resistance *R* is on one side and the moving wire on the other, is there any e.m.f.?



2. A certain two-pole machine with ring armature winding operates with separately excited field. How will the polarity of the brushes be affected (*a*) if the direction of rotation were reversed? (*b*) If the field current were reversed? How will the amount of e.m.f. be altered (*c*) if the speed is halved? (*d*) If the field current is doubled? How will the e.m.f. be affected (*e*) if a set of brushes (positive and negative) is placed on the commutator at the neutral position? (*f*) If this set of brushes is swung around the commutator from the neutral position, but always keeping on a diameter?

3. A bipolar dynamo has a ring-wound armature, with the coils properly connected to the commutator, to generate a continuous current. There are 200 turns of wire on the armature and 6,250,000 magnetic lines through the armature. When the armature revolves at 1200 r.p.m., what number of volts are generated in the armature?

4. A certain two-pole dynamo with ring armature has 84 commutator bars and 10 turns per coil of winding. It is running at 1800 r.p.m. and generating 250 volts. How much flux must be coming out of the *N* pole? (Use the e.m.f. formula and get instructions for transposing letters so Φ stands alone on the left-hand side.)

5. A separately excited dynamo is running so its generated e.m.f. is 125 volts. There is a rheostat in series with the field in which 20 per cent. of the 125 volts available for field excitation is used up. The resistance of the field is 25 ohms. What change in the e.m.f. if the rheostat is cut out?

6. A shunt dynamo has been working with 6000 turns in the field winding and 1¼ amp. through them. It is proposed to rewind the field coils of the machine so that as a series dynamo under full load of 375 amp. the same volts as before will be generated. How *many* turns should be put into the winding?

7. A certain short-shunt compound dynamo has 2200 turns in the shunt field winding and 20 turns in the series winding. Before the main circuit is closed 3 amp. flow in the shunt winding. At full load there are 3.2 amp. in the shunt winding and 150 amp. in the series winding. How does the strength of the magnetic field at full load compare with that at no load? Neglect saturation effects.

8. A certain dynamo has 110 volts at its terminals when delivering 200 amp. If the armature resistance (from + to − brush) is 0.011 ohm, how many volts e.m.f. is it generating?

CHAPTER V

DRUM ARMATURES AND MULTIPOLAR MACHINES

41. Drum Armature for Two-pole Machine.—The winding for a two-pole dynamo is put on a core like that of the upper part of Fig. 38. The winding is done in two layers and the method of placing it and of making the connections can be determined by noting the markings of Fig. 51, and following the tabulation below. Each coil is shown as of one turn. The number of turns actually used is always enough to entirely cover the armature with at least two layers of winding.

	Bar	Winding	Bar
Coil No. 1	1	up to *a* back and across to *b* around to	2
Coil No. 2	2	up to *c* back and across to *d* around to	3
Coil No. 3	3	up to *e* back and across to *f* around to	4
Coil No. 4	4	up to *g* back and across to *h* around to	5
Coil No. 5	5	up to *i* back and across to *j* around to	6
Coil No. 6	6	up to *k* back and across to *l* around to	7

The first layer of winding is now in place and the armature surface is covered. Connections to one side of the commutator are entirely completed. The coils have been wound across a diameter but have in other respects been connected as for a ring armature. The second half of the winding is put on thus:

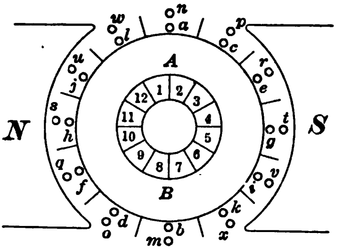


FIG. 51.

	Bar	Winding	Bar
Coil No. 7	7	up to *m* back and across to *n* around to	8
Coil No. 8	8	up to *o* back and across to *p* around to	9
Coil No. 9	9	up to *q* back and across to *r* around to	10
Coil No. 10	10	up to *s* back and across to *t* around to	11
Coil No. 11	11	up to *u* back and across to *v* around to	12
Coil No. 12	12	up to *w* back and across to *x* around to	1

A complete closed winding is thus finished. Every coil has e.m.f. induced in it except No. 1 and No. 7. The neutral line for this armature is on a vertical line and the proper position for the brushes will be with one resting where it will short-circuit the coil between bar 1 and bar 2, while the other short-circuits the coil between bars 7 and 8. It then follows that the full voltage of the machine is found between coils in the two layers which lie immediately over one another. On this account careful insulation of one layer from the other must be made. If in Fig. 51 we assume that a full winding is shown and that 2 volts are generated in each wire except in coils *ab* and *mn*, the machine produces 20 volts and supplies current through two parallel paths. The direction of e.m.f. is indicated in the various conductors for this armature (Fig. 52) by using the common convention that a dot shows an e.m.f. directed out toward us (the point of an arrow), while a cross indicates an e.m.f. directed away from us (the tail of an arrow). Noting again the way in which the coils are connected it will be seen that the upper brush will be positive and the lower negative for the direction of rotation marked.

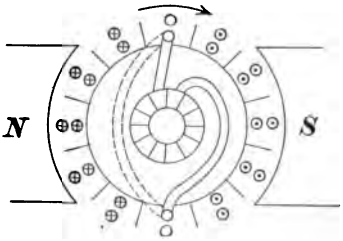


Fig. 52.

For drum armature windings it does not always follow that the line on which the brushes are placed should coincide with the neutral line of the winding. In Fig. 53 is shown a method of making commutator connections quite as good as the one of Figs. 51 or 52, but in this case the proper position for the brushes where no armature reaction is present will be on a horizontal line *XY*, as marked.

The two-pole drum armature winding now described would only be found on very small machines; and then it would be on a toothed armature core. Since multipolar drum armatures are in almost universal use, no more space will be given to a discussion of the winding for a two-pole machine.

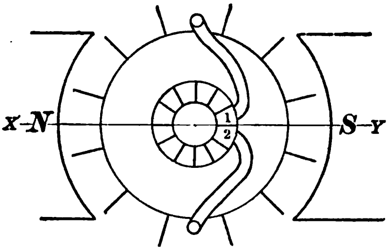


Fig. 53.

42. Toothed Armature Core.—A toothed armature core is built up of sheet-steel discs in the outer periphery of which teeth have been cut. The armature windings are placed in the slots which are almost invariably straight sided and the same

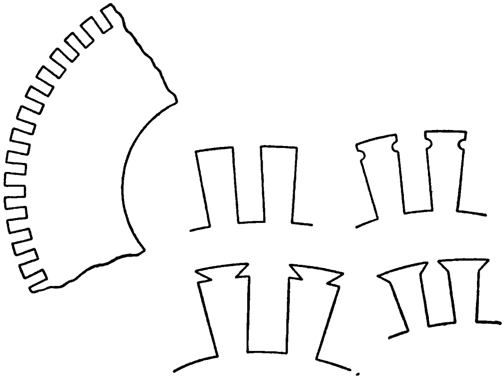


Fig. 54.

width from top to bottom. This makes the teeth tapering toward the roots. Different forms of teeth in regular use are shown in the lower part of Fig. 54. Some of the main advantages of toothed armatures are the following:

(*a*) A toothed armature is a much better mechanical structure than a smooth core armature.

(*b*) With multipolar machines, cheaper labor can be used in constructing the armatures, and repairs are relatively easy.

(*c*) Every coil can be exactly like every other; and they can be separately constructed before the winding is put on.

(*d*) By careful design of the teeth with reference to the flux intensity permitted in them, the effects of armature reaction can be minimized.

A toothed armature core, ready to receive the coils of winding, is shown in Fig. 60. In such machines as this the core plates do not come near the shaft; they are supported as shown in the lower part of Fig. 38, although this does not show well in Fig. 60 on account of the projecting end discs which are designed to support the end connections of the winding.

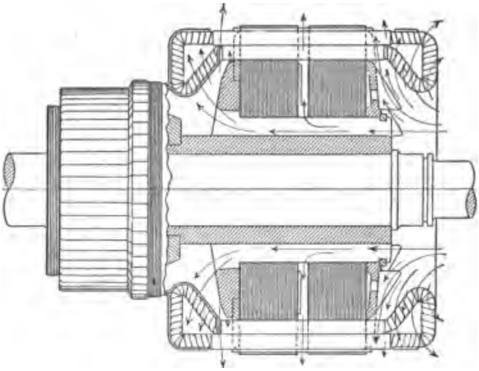


Fig. 55.

Fig. 55 shows this somewhat better. When the armature core is constructed this way the spider is made of cast iron and in all the best machines there is a projection cast on the hub for the purpose of supporting the commutator. This makes the whole armature and its connections a separate whole which can be removed from the shaft if desired. Fig. 55 also shows how the core is arranged so abundant air circulation can take place when the armature is running. This is an important aid in cooling it (next chapter explains cause of heating). In Fig. 60 the two dark lines in the body of the core show where ventilating ducts have been left through the core stampings.

43. Multipolar Drum Armature Lap-winding.—Fig. 56 shows an outline of a drum armature in a four-pole field. On it are placed some conductors marked with the direction of e.m.f. induced in them for polarity and direction of rotation shown. A dot means e.m.f. directed toward the reader; a cross, the e.m.f. directed away from the reader. It will be noted at once that if they are to be cross-connected to form coils, the span must be only one-quarter of the armature circumference in order that the e.m.f. generated in the two sides of a coil shall always be in series around the coil; and also in order that there are positions where there is no e.m.f. in a coil and it can be short-circuited. The loops *ab* or *cd* generate e.m.f. so that what is produced in one side is added to that of the other, while loop *ef* has no e.m.f. in it, and so could be short-circuited.

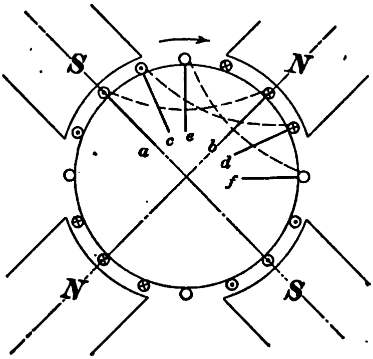


Fig. 56.

Fig. 57 shows how a lap-winding is arranged. It is wound in two layers. The back connections are not shown; but *A* and *A′* are the two sides of the same coil and this method of marking is used for every coil shown in the diagram. Starting from commutator bar 1, a coil can be wound by going to conductor *A*, around on the back and through *A′* down to bar 2. If more than one turn per coil is used, after passing through one, return to *A* again and continue until the required number of turns are in place; then connect the last end to bar 2. The coils which are used for such a winding are formed coils, samples of which are shown in Fig. 58. The ones shown have three complete turns per coil of double cotton-covered wire, wrapped with cotton tape to form the coil, and afterward varnished or impregnated to keep moisture out. The projecting ends for commutator connections have cotton sleeving over them to reinforce the insulation there. A careful inspection of these coils and of Fig. 61, in which a number of such coils are shown in place, will show how one side of each coil (the left in this case when facing the commutator) goes in the top layer of the winding and the other side in the bottom layer. By this plan all the coils are exactly alike and the crossing of end connections is easily and neatly arranged. A winding of the sort shown in Fig. 61 with end connections carried straight out rather than cranked down toward the shaft is called a barrel winding.

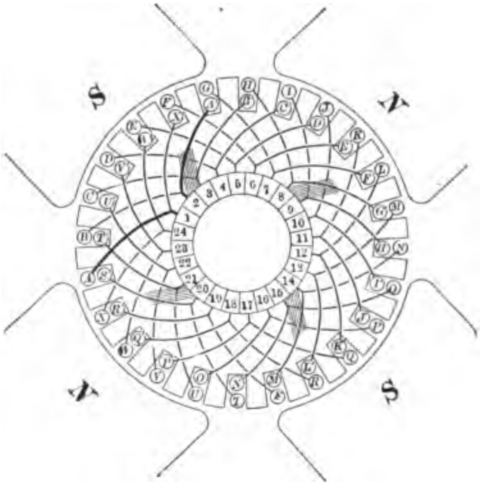


Fig. 57.

In Fig. 57 the coils are put on according to the following plan:

	Bar	Winding	Bar
Coil No. 1	1 front connection over to *A*	back and across at rear to *A′*	forward and down to 2
Coil No. 2	2 front connection over to *B*	back and across at rear to *B′*	forward and down to 3
Coil No. 3	3 front connection over to *C*	back and across at rear to *C′*	forward and down to 4

This continues until the armature is filled with coils and the last coil end connects to bar 1. In putting the last coils in place sides *A*, *B*, *C*, etc., have to be raised out of the way while the lower layer is finished. They can then be pushed back into place. There will be as many slots as coils and the same number of commutator bars.

It should be noticed how the ends of every coil end on adjacent commutator bars and that each succeeding connection laps back over those put down before. In winding an armature none of the commutator connections are made until the whole winding is in place. They are then taken in regular order and soldered to the commutator bars.

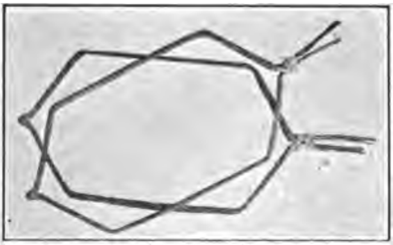


Fig. 58.

After passing through one-quarter of the coils on the armature the e.m.f. reverses. In the armature of Fig. 57 the coils in series from commutator bar 3 to 8 are generating e.m.f. all one way—from 8 toward 3. At 2 volts per wire, 20 volts are generated. Coil *HH'* from bar 8 to 9 generates nothing and then the e.m.f. reverses. We saw in a two-pole machine that this is the place where a brush should stand. A − brush then belongs at the place where bars 8 and 9 are short-circuited. By similar reasoning it will easily be seen that there are four brush positions on the commutator. Turning now to Fig. 59 which represents the same armature again but with winding detail omitted, we know that brushes *A* and *C* are negative and *B* and *D* are positive. We also know that we can join brushes *B* and *D;* for the volts from *C* to *B* (in the winding) are equal and opposite to those from *C* to *D*; and those from *A* to *B* are equal and opposite to those from

A to *D*. Hence no current could flow in this cross-connection. For a similar reason *A* and *C* can be joined. This having been done, *F* and *G* become machine terminals between which 20 volts e.m.f. is derived. Current delivered by the dynamo flows through four parallel paths in the winding. Coming in from the outside circuit to *F* the current divides, half passing to *A* and half to *C*. At *A* this redivides into equal portions, each quarter of the whole, one portion passing through quarter of the winding toward *D*, and the other portion passing through another quarter to *B*. The other paths are easily traced.

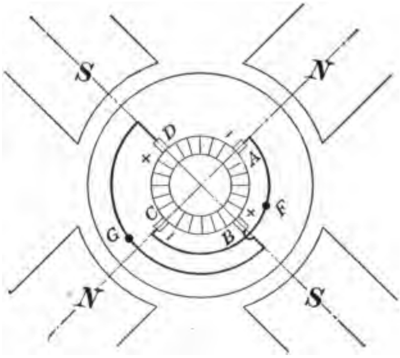


Fig. 59.

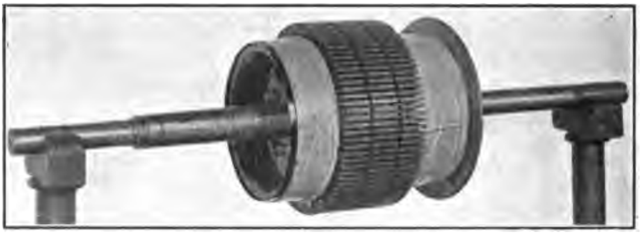


Fig. 60.

A multipolar lap-wound drum armature winding always has as many paths through the armature winding as there are poles, and uses as many brushes as poles. The brushes are placed at even intervals around the commutator, positive brushes alternating with negative. All the positive brushes are cross-connected, and all the negative brushes also.

The armature winding described above is by no means the only arrangement of a multipolar drum armature lap-winding. In a practical machine many more coils could be placed on a core containing more slots. Sometimes different spacing for coils is used. Sometimes more than two sides of coils are placed in the same slot. Sometimes commutator connections are differently managed. But if the winding herein is well understood, others will be recognized as simple modifications.

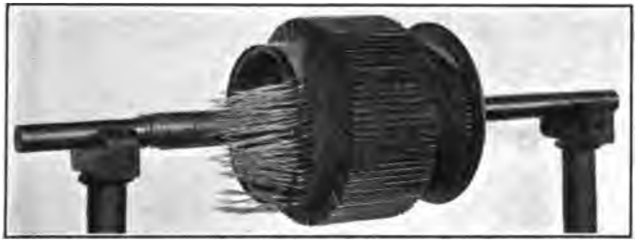


Fig. 61.

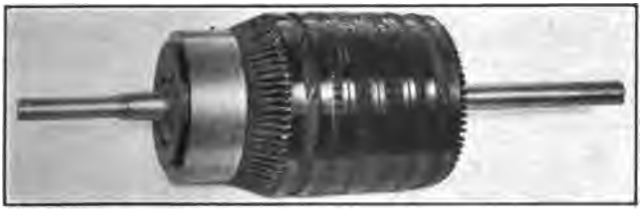


Fig. 62.

44. Frame and Bearings.—Fig. 63 shows the machine complete, ready for use. Here the lower half of the magnet frame is cast in one piece with the base frame and pedestal bearings. The rails and adjusting screws to allow adjustment to suit the stretch of the belt as it runs on the pulley, are shown in place.

One of the important mechanical features of a dynamo is the bearing and oiling device. A bearing similar to that in Fig 64 is used on all dynamo machines. Note the cast-iron casing built to receive the bearing proper, which is a spherical seated one. That is, it is made with a segment of a sphere turned on its middle portion and this rests in a corresponding seat. At each side there is a slot in which hangs a light brass ring which dips in the oil reservoir below and by rolling on the shaft as it rotates brings up a constant supply of lubricating oil. An oil gage to show the height of the oil appears on the pedestal. The bearing cap is omitted in the cut.

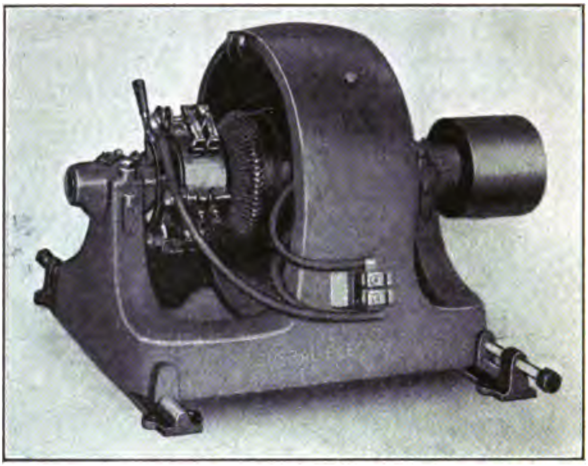


Fig. 63.

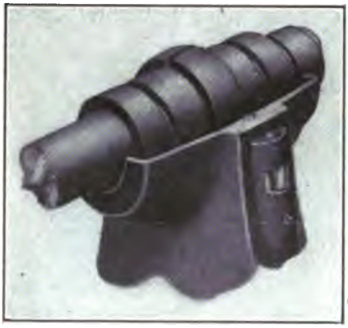


Fig. 64.

45. Multipolar Drum Armature Wave-winding.—Another form of drum armature winding in common use, must be briefly described.

In Fig. 65 is an outline of a multipolar wave-winding for a four-pole dynamo. In some respects this winding is precisely like the lap-winding described in the last section. Formed coils are used, and the winding is in two layers. The forms of the coils are different, however, as may be seen by inspection of Fig. 66, where coils with three different sorts of end formation are shown. When more than one turn per coil is used, the ends leave the coil along its sides and not as shown for coils forming part of a lap-winding in Fig. 58. Inspection of Fig. 65 will show why this is done and what is the nature of this winding. A coil would be started from commutator bar 1, then pass up to *A*, through the slot and across on the back to *A′* (lower layer), back to *A* again and so continue until the proper number of turns were wound, the last end being taken from *A′* to commutator bar 12. From here we go to a coil laid in from *B* to *B′* with its last end connected at bar 23, next to the one from which we started. The winding goes on continuously in the same way and it may be traced out from the diagram or followed by the aid of this tabulation:

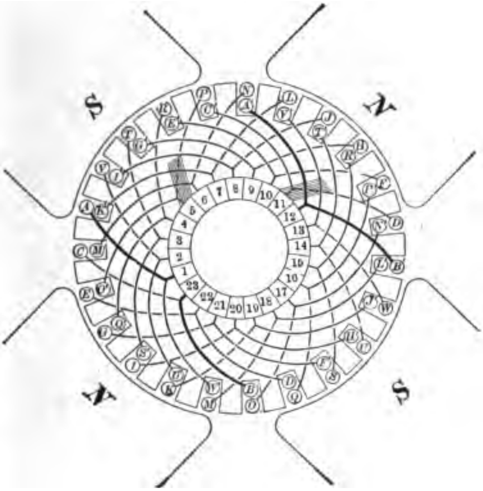


Fig. 65.

	Bar	Coil winding	Bar
Coil No. 1	1	to A across on the back to A' forward and down to	12
Coil No. 2	12	to B across on the back to B' forward and down to	23
Coil No. 3	23	to C across on the back to C' forward and down to	11
Coil No. 4	11	to D across on the back to D' forward and down to	22
Coil No. 5	22	to E across on the back to E' forward and down to	10
		etc. etc.	

After passing through all the coils the last end reaches bar 1 from which we started. If an investigation were made of the direction of the e.m.f. in all the wires cutting flux it would turn out that by this method of winding half the winding must be passed through before a place is reached where the e.m.f. reverses. That is, if we start from commutator bar 5 we will have traversed half the coils generating e.m.f. in series when we reach bar 11, and passing on through the coils will reach bar 5 again as the other half of the winding, and its e.m.f. is passed. Hence we place a brush at bar 5 and another at bar 11. No more are required. It is impossible to short-circuit any coils in the winding shown without involving some e.m.f. in the short-circuit connection. This would not be true for an armature built with two or three times as many commutator bars and coils.

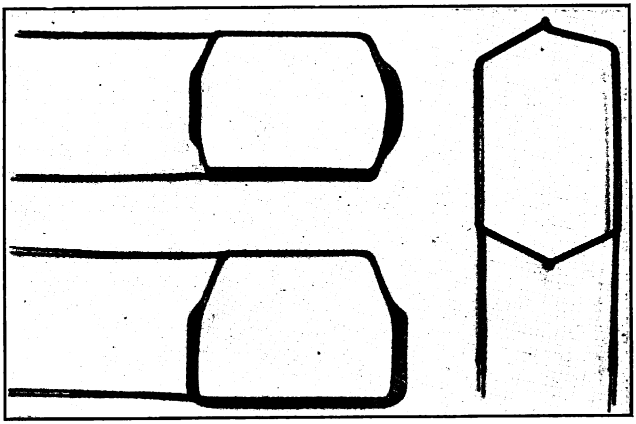


FIG. 66.

This winding carries half the main current in each of two parallel paths through the armature (compare the lap-winding) and generates twice the e.m.f. of the other if wound with the same coils. Fig. 65 shows an armature with 23 coils and commutator bars. For a four-pole dynamo the number of commutator bars is always odd.

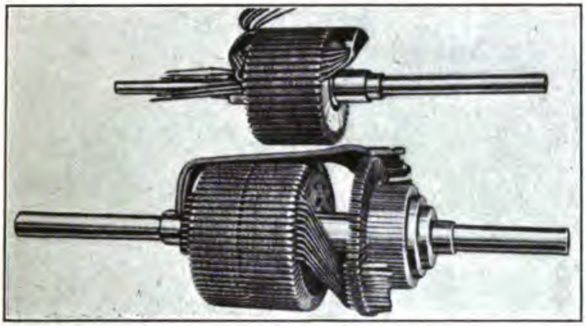


FIG. 67.

Fig. 67 shows wave-wound armatures with a few coils in place. The upper part of the figure shows coils similar to those of Fig. 66. The lower one shows a winding with only one turn per coil. Fig. 68 shows completed wave-wound armatures in which the coils are so formed that the rear cross-connections are

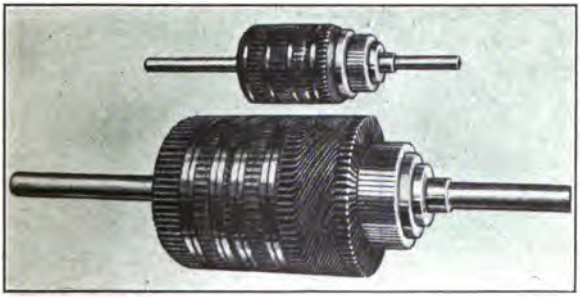


FIG. 68.

cranked toward the shaft. Fig. 69 shows one with a barrel winding.

If desirable there may be as many brushes as poles with this type of armature. This does not alter any of the connections or the flow of current. For, suppose a brush is placed on bar 15 and cross-connected to one on bar 5, through this cross-connection there is only a short-circuit placed on a coil (*P* to *P′*) not generating any e.m.f. Hence brushes may be placed and cross-connections used as for lap-windings if desired. Sometimes they are, sometimes not used.

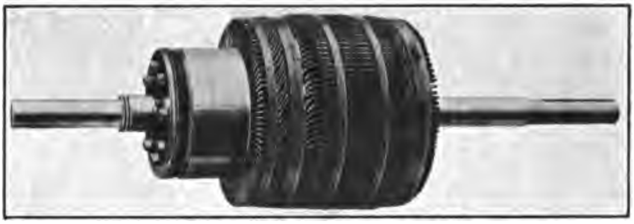


Fig. 69.

46. General Features of Drum-windings.—For all drum armatures the facts explained fully in the previous chapter about location and function of the brushes, neutral line, and armature reaction, hold as true as for ring armatures. The neutral line is determined the same way, as the place in the winding where no e.m.f. is generated; and for multipolar machines it becomes a line midway between adjacent pole tips, all the way around the armature.

The formula of section 39 for the amount of e.m.f. generated in a ring armature winding holds good for a multipolar drum armature with lap-winding if Φ stands for the flux out of any single North pole. For a multipolar wave-wound drum armature a simple adaptation can be made.

Thus for a 4-pole machine:

The average e.m.f. generated in one conductor in volts is

$$E = \frac{4\Phi n}{100,000,000}$$

The number of conductors in series is $\frac{c}{2}$ for a wave winding and so

$$\text{e.m.f. of dynamo} = \frac{4\Phi n}{100{,}000{,}000} \times \frac{c}{2}$$
$$= \frac{2\Phi cn}{100{,}000{,}000}$$

QUESTIONS AND PROBLEMS

1. A drum armature in a two-pole field has 6 turns per coil, 52 commutator bars, a flux of 1,600,000 lines, and is running at 1050 r.p.m. How many volts will be generated?

2. A small Westinghouse bipolar drum armature has 50 slots. In each one are 8 wires. The normal speed of the machine is 2100 r.p.m. and flux through the armature 835,000 lines of force. How much e.m.f. is generated?

3. A maker uses the same armature core for a 125-, 250-, and 500-volt machine of the same capacity. To generate 125 volts 144 turns of No. 8 wire are used. What number of turns (and if possible what size wire) for 250 volts to be generated? For 500 volts? The field winding and current are supposed to stay unaltered.

4. In a certain position, while revolving at normal speed and on account of an unsymmetrical winding, a drum armature in a two-pole field has 110 volts generated in one side when 105 volts are generated in the other. There are 250 ft. of No. 10 wire on the armature. Will any current flow when none is being delivered to an outside circuit? Make a calculation.

5. A certain armature for a four-pole field has a drum-winding. How could this be determined by observation? It has 115 commutator bars. What sort of drum-winding must it be and how many sets of brushes would you expect around the commutator?

6. A certain armature when examined is found to have 104 commutator bars and 52 slots in the toothed core. Explain how this could be for a drum-winding to be used in a four-pole field. Upon examination it is found to have a double layer winding. Is this practical? If there are 2 turns per coil, how many wires are there in each slot?

7. Make two diagrams showing in outline in each a cylindrical armature large enough to draw some coils in place as in Fig. 56 and place the poles around each armature. On one draw in 3 or 4 coils of lap-winding with commutator connections so placed that the brush positions will be opposite the center of the poles. On the other draw the connections so brush positions will be opposite the spaces between the poles. Mark a proposed direction of rotation and the + brushes.

8. A four-pole dynamo has a multipolar lap-wound drum armature. 160 amp. flows from the armature to field winding and outside circuit. How much current is flowing in each wire of the winding? How much would it be if the winding had been multipolar wave-wound?

CHAPTER VI

ELECTRIC HEATING. ELECTRIC POWER

47. Energy.—Energy is defined as internal or inherent power; the capacity of acting, operating, or producing an effect whether exerted or not.[1] In engineering applications it is understood that anything has energy if it has the ability to do work. Energy really means the same whether applied to animate or inanimate things.

Suppose a weight is lifted. Work is done on it—it has in this way acquired the ability do to work. A falling weight can do work we know. A simple example is a weight driving the works of a clock, the mechanism being kept under restraint by a pendulum. In any case a falling weight does work in falling. Thus, if it were to fall on some lumber, smashing it, work is done as much as if, in falling, machinery had been driven which would saw it up.

The energy which a weight has because of its location and which it delivers by falling, is mechanical energy. There are a number of other forms of energy which are mentioned later (section 51).

48. Force.—The weight referred to in the last section exerts a force whether moving or not. A force is that which, acting on a material body, moves it or tends to move it. If a weight were hung on a spring balance the balance would show some reading. If we hook the same balance to something stationary and pull, it can be made to show the same reading. As this is done by exerting force, the weight also exerted a force measured by the reading of the balance. The force exerted (the pull of gravitation) is the number of pounds the object weighs.

49. Work.—In every case when force acts through distance work is done; and the work done (W) is the product of the force (F) by the distance (s).

$$W = Fs$$

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[1] Webster's International Dictionary.

The amount of work done is measured in a unit known as the foot-pound (ft.-lb.). If a weight of 50 lb. is raised 10 ft., 50 × 10 = 500 ft.-lb. of work have been done. The same amount of work is done in lifting 500 lb. 1 ft.

A large number of practical examples can be suggested illustrating work done in this way. Any elevator or hoist, a pile driver, an ordinary block and tackle, are appliances for doing work this way.

It is not necessary to lift weights in order to do work. Suppose we have a locomotive pulling a train of cars. A spring balance (called in such case a dynamometer) set in between the locomotive and the cars would show a pull of a good many pounds (the draw-bar pull) as the cars were pulled along the track. This is the force the locomotive exerts on the train. The product of the pull on the dynamometer by the number of feet the train was pulled would show the work done by the locomotive in pulling it over this distance.

A Pullman coach weighs some 60 tons. A train of five of them make up a train. It takes some 10 lb. per ton to pull cars over a level track. The dynamometer between locomotive and cars for this train would show 3000 lb. force exerted. In running a mile the work done would be

$$W = 3000 \text{ lb.} \times 5280 \text{ ft.} = 15{,}840{,}000 \text{ ft.-lb.}$$

The work done in any operation is independent of the time spent in doing the work. It makes no difference in the above example whether the locomotive is running 10 miles per hour or 60, the work done is the same.

50. Power.—By power we mean the rate of doing work; that is, the rate of spending energy.

$$\text{Power} = \frac{\text{work}}{\text{time}} \text{ or } \frac{\text{energy}}{\text{time}}$$

Hence power is measured by foot-pounds per minute or per second. The rate of doing work is 1 hp. when 33,000 ft.-lb. are spent per minute.

Taking the example in small print in the last section, suppose the Pullman train there mentioned was carried over the mile at the rate of 15 miles per hour. It would take 4 min. to make the distance. Hence

$$\text{power developed} = \frac{15{,}840{,}000}{4} = 3{,}960{,}000 \text{ ft.-lb. per minute}$$

or

$$\frac{3{,}960{,}000}{33{,}000} = 120 \text{ hp.}$$

If the train was running at 60 miles per hour, or a mile a minute, the power developed would be

$$\text{power} = \frac{15{,}840{,}000}{33{,}000} = 480 \text{ hp.}$$

51. Transformation of Energy.—There are various forms of energy. Some are stated below along with an example of a piece of apparatus which uses it.

(*a*) *Mechanical.*—A pile driver, by means of which a falling weight does work.

(*b*) *Heat.*—A steam engine, by means of which the heat energy of steam is made to drive machinery.

(*c*) *Chemical.*—A cannon, by means of which the energy of chemical combination of gun powder is made to drive a projectile through a target.

(*d*) *Electrical.*—An electric motor, by the operation of which industrial processes are carried on.

Each of these forms of energy can be turned into any one of the other forms. In practical transformations it is impossible to have all the energy of one kind transferred into another kind. Some loss always accompanies the transformation. For example, the chemical combination of gunpowder not only furnishes mechanical energy to drive the projectile through a target, but furnishes energy to heat the products of the combination and the gun, and to produce the report at discharge.

A very definite relation has been established experimentally between mechanical and heat energy. A definite relation also exists between electrical energy and heat energy. It is important at this point to secure definite ideas about heat in order to make these relations clear.

52. Temperature.—The use of the word temperature is so common that no formal definition need be given. If a body is warmed we speak of its having a higher temperature, and can measure this by a thermometer.

The ordinary thermometer uses the expansion due to the heating of some liquid in a glass tube of uniform bore to indicate temperature. The Fahrenheit thermometer has a mark put at the height of the expanded liquid when immersed in boiling water, and one at the height of the liquid when immersed in melting ice. The upper mark is called 212 degrees and the lower 32 degrees; the space between is divided into equal intervals to show intermediate temperature. If desired, marks below 32 degrees at the same intervals are put on the tube to mark lower temperature.

The Centigrade thermometer has 100 degrees put at the boiling point of water and 0 degrees at the melting point of ice. It is used a good deal in temperature measurements connected with engineering work. Twenty degrees Centigrade (C.) is about the same as 70 degrees Fahrenheit (F.).

$$\text{Temperature Cent.} = \tfrac{5}{9}\,(\text{temperature Fahr.} - 32).$$
$$\text{Temperature Fahr.} = \tfrac{9}{5}\,(\text{temperature Cent.} + 32).$$

53. Heat.—When the temperature of any body is raised we know it has been heated; that is, heat has been given to it. Bodies have temperature because they contain heat. Heat can be given to a body by conduction (as when an iron bar is heated by being placed in a fire), by radiation (as when an object near a furnace is heated even though air currents are directed from it toward the furnace), or by convection (as when a crucible is heated by the gases of combustion which carry their heat to the crucible as they pass to the flue of the furnace).

If two vessels exactly alike were placed near a source of heat so that the radiation to both would be the same and filled one with water and the other with bird shot at the same temperature, after a time the shot would be warmer than the water. This shows that the same amount of heat will not raise the temperature of different materials the same amount. A pound of water takes more heat to raise its temperature 10° than a pound of lead.

Putting heat into a body does not necessarily raise its temperature. Thus, if water is heated the temperature rises until boiling begins; and then no further rise in temperature occurs while heat is continually supplied. This is because the water is undergoing a change of state, passing from water to steam, and this requires considerable addition of heat. These things are mentioned in order to aid in making clear the relations between heat and temperature. Heat and energy have direct relation; heat is measured mainly by temperature observations. The unit of heat is the amount which is required to raise the temperature of one pound of water 1°F.[1] It is known as a British thermal unit or B.t.u. If we had 100 lb. of water and were to heat it from 50° to 212°, $(212 - 50) \times 100 = 16{,}000$ B.t.us. must be supplied.

54. Mechanical Equivalent of Heat.—It is a matter of common observation that heat and work are easily converted into one another. If we rub a steel tool on a grindstone the tool gets hot. The work we are doing is being transformed into heat. A steam engine takes steam at a high temperature (say 300°F.), and having used it to do work exhausts it at 212°F. The heat of the steam has been transformed into work. Careful experiments have shown that 778 ft.-lb. of work must be done to produce 1 B.t.u. or, conversely, that the expenditure of 1 B.t.u. of heat can produce 778 ft.-lb. of work. Most prime movers are heat engines by means of which heat is converted into mechancial work.

55. Efficiency.—As already stated (section 51), a transformation of energy is never effected without loss. The loss of energy is often in the form of heat. Take any piece of machinery designed to perform some useful work, and a large amount of the work done is spent in driving the machine itself—against its own frictional resistance, as we say. A considerable expenditure of power is required simply to drive the machine when it is running empty, that is, without doing any useful work. The energy spent is lost in heat at rubbing surfaces—teeth of gear wheels, in bearings, where belts rub on pulleys, etc. Some rise of temperature at each such place results, which does not usually become serious, since radiation and conduction pass this heat on as it is produced.

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[1] There are other heat units; the one here given is that used mostly in mechanical engineering work. The reader should not attempt any general application of it to numerical problems unless he has a much wider knowledge of the subject than here given.

The efficiency of any apparatus is the *ratio of the energy delivered by it to the energy supplied to it, expressed in per cent.*

$$\text{Hence, efficiency} = \frac{\text{energy delivered by it}}{\text{energy supplied to it}} \times 100$$

$$\text{or} \quad = \frac{\text{energy delivered}}{\text{energy delivered} + \text{the losses in the machine}} \times 100.$$

To illustrate this further, consider the usual set of energy transformations found in the ordinary central station lighting system. Start with the heat produced in a steam boiler furnace by combustion of the fuel. About 30 per cent. of the heat passes up the chimney and is lost by radiation. Seventy per cent. is, therefore, the efficiency of energy transformation from heat of combustion to heat of high-pressure steam in the boiler. The steam passes from the boiler through pipes to the steam engine. In them 10 per cent. of the heat is likely to be lost by radiation from the pipes. The efficiency of the pipes then is 90 per cent. The steam passes on into the engine where a small part of the heat energy is transformed to mechanical energy. Only a small part is transformed because the steam must pass through the engine as steam, while a very large amount of heat is required to change water to steam in the boiler, none of which heat can be made use of. Say 92 per cent. of the heat delivered to the engine is lost in this way or it has an efficiency of 8 per cent. Not all of the mechanical energy produced in the engine can be passed on to the dynamo it drives, for the engine has bearings in which, in spite of lubrication, some heat is developed, and so energy is lost. The engine may have an efficiency of 95 per cent. By driving the dynamo the engine supplies mechanical energy which is converted into electrical energy (see next section) and some of this is lost by heat developed in the dynamo. The dynamo may have an efficiency of 92 per cent. Current flowing out into the wires on the way to lights heats them, and a loss of energy occurs; the line may have an efficiency of 90 per cent. or more. In an electric light from 92 to 95 per cent. of the electrical energy supplied is lost in heating the source to incandescence and so its efficiency as a light producer is only 5 to 8 per cent. Putting this whole thing together, the efficiency of transformation of the energy of coal to that of light is only .25 per cent. At the same time we have been observing the nature of efficiency itself, we have been noting by this example how poor are our best modern methods of energy transformation.

56. Heating Effect of Current.—It is an experimental fact that a conductor through which electric current passes is warmed by it. A large conductor with small current flowing in it may be warmed so little that the rise of temperature is very difficult to detect; while a small conductor with large current through it may be heated to the melting point. If the current in a conductor is doubled, the rise in temperature (measure of heat liberated) is much more than doubled. Careful investigation has shown that the *heat produced by current flowing* in any conductor is proportional to the resistance of the conductor, to the time the current flows, and to the square of the amount of current flowing. Let us examine each of these relations carefully.

If we have two conductors in series (both have thus the same current through them) and one (A) has twice the resistance of the other (B), A will have twice as much heat developed in it as B. This does not imply that the temperature of A will rise twice as much as that of B. For the rise of temperature is determined by the amount and kind of material heated and its surroundings as much as by the resistance which it has. If A and B are pieces of the same wire similarly placed, A would have no higher temperature than B even though it has twice the resistance, since to bring it to the same temperature twice as much heat must be developed, for it has twice as much material as B; it is twice as long.

The heat produced is proportional to the time current flows, for it must be that if a certain current produces a certain amount of heat in a conductor in any one second it must produce the same in any other. But the temperature of a conductor through which current flows will not keep on rising indefinitely. As the temperature rises a greater proportion of the heat which is being constantly produced gets away by conduction, radiation, and convection; and presently, unless the conductor melts and opens the circuit, a steady temperature is reached. In most electrical apparatus conductors are so chosen that their rise in temperature will be quite moderate. By suitable choice of conductors it is easy to have one part of a series circuit white hot, while another part close by is quite cool. Examples are found in any circuits containing lights or heating apparatus.

The heat produced is proportional to the square of the current flowing. Hence, doubling the current causes four times the production of heat. If a certain conductor from which no heat at all escapes, is warmed 8° by the passage of 5 amp. for six minutes, then if 10 amp. flow, the rise of temperature would be 32° in the same length of time.

57. Electrical Energy and Power.—The heat produced by the flow of current must be derived from electrical energy represented by its flow. If we put the general statements of the last section into a formula we have the following to express the electrical energy which is transformed into heat:

$$\text{energy} = I^2Rt$$

where I and R have the usual significance of amperes and ohms respectively and t stands for time. Using a formula from section 50 we can write

$$\text{power} = \frac{\text{energy}}{\text{time}} = I^2R$$

$$\text{power} = IR \times I$$

By Ohm's law we know that $E = IR$. Hence

$$\text{power} = EI$$

In words, electric power is the product of volts by amperes. The unit of electric power is the watt. Hence,

$$\text{volts} \times \text{amperes} = \text{watts}.$$

If a lamp is supplied with ½ amp. at 110 volts, it is using 110 × ½ = 55 watts of power. If a dynamo is delivering 800 amp. at 125 volts, the electric power it is sending into the circuit is 800 × 125 = 100,000 watts. In much commerical work the numbers to express power in watts become so large that another unit, the kilowatt, is much used. One thousand watts equal one kilowatt (kw.). The dynamo mentioned above under the conditions stated would be supplying 100 kw. to the circuit.

Another unit of power, the horsepower, has already been mentioned. A simple numerical relation connects the two. 746 watts = 1 hp. To determine how many horsepower are represented by 100,000 watts divide by 746.

Power is the rate of doing work or the rate of supplying or spending energy. Let us seek a unit for the measurement of electrical energy:

$$\text{power} \times \text{time} = \text{energy}$$
$$\text{watts} \times \text{hours} = \text{energy}$$

The usual unit of *measurement of electrical energy* is the watt-hour. For large use of energy the kilowatt-hour is the unit.

Thus, suppose a lamp using 55 watts is burned 5 hr. each day for 6 days; how much energy has been used? It has been in use 30 hr. and so 55 × 30 = 1650 watt-hr. have been used. The thing which a central station engineer wants to know is the amount of energy a customer has used. This has a definite relation to the coal which has been burned to supply his need. It is not of great consequence whether he makes use of current steadily or intermittently, over short or long periods (the maximum rate of supply allowed is guarded separately). Hence, the charge to the customer is based on a certain price per kilowatt-hour and the meter installed at customers' premises to register his use of energy usually records this directly.

58. Dynamo Efficiency.—A dynamo is a machine for the transformation of mechanical to electrical power. When running on open circuit an e.m.f. is generated but no power is transformed. As soon as current flows through the armature the product of the current flowing by the generated e.m.f. gives the power the machine is producing. All of this does not reach the external circuit. The product of the current to the external circuit by the terminal difference of potential expressed in watts or kilowatts is called *the load.*

In every dynamo the power losses make the power delivered by the machine considerably less than the power supplied to it. The various losses may be considered separately.

1. The winding losses. The power gone in heating the armature winding, and the field winding. That for the armature, for example,

would be calculated by multiplying the armature resistance by the square of the current flowing there.

It is to keep the field-winding loss small that the shunt field has so many turns of small wire which keep down the amount of current flowing; for precisely the same reason the series field is made of heavy conductor of very low resistance.

2. The heat loss in brushes and connections and terminals. Current flowing through them causes a loss of power; the liberation of heat sometimes causes a large rise in temperature.

3. The mechanical friction loss; the power gone in bearing friction, brush friction on the commutator, and windage of the armature (the fanning effect due to irregular surfaces and forced ventilation).

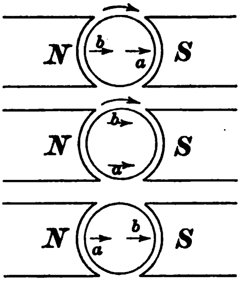


Fig. 70.

4. The hysteresis loss. The iron core of the armature as it rotates experiences a change in the direction of flux through it. In Fig. 70 at *a* and *b* small arrows stand for iron molecules. In successive diagrams the positions of these molecules are shown. It will be clear that each molecule through which flux passes from the *N* to the *S* pole rotates, in the case of a two-pole machine making one rotation for each revolution of the armature. This causes internal molecular magnetic friction and generates heat. The amount varies with the kind of iron used and the flux intensity.

5. The eddy-current loss. The cause of these currents and the way they flow has already been shown in section 38. Such currents flowing generate heat (I^2R) and raise the temperature of the armature. They are likely to be found in every metal part of the armature. The teeth of a toothed core, however, shield the conductors from having eddy currents generated in them.

The efficiency of a dynamo alters with the load it carries. This is because some of the losses are constant for all loads and therefore relatively large on light load. The efficiency varies with the size of a dynamo. A small machine with a 1-kw. capacity is not likely to have an efficiency greater than 70 per cent. A 100-kw. machine may have an efficiency as high as 92 per cent.

59. Dynamo Capacity.—Every machine is marked for a certain power development. The amount of energy it can transform involves the length of time it is kept operating. This power development is based on the *heating and sparking limit* of the machine. A machine is said to have reached its heating limit when the heat produced in it has raised its temperature so that any greater heating (resulting from more current flowing) would endanger the machine, due to scorching the insulation or unsoldering of connections to commutator; in short, produce a risk of "burn out." In common practice the heating limit is set at 40°C. rise in temperature above that of the surrounding air. A dynamo is expected to operate continuously, developing the power marked on the name plate without a rise of temperature more than this, unless it be at the commutator where 5° more may be expected. The sparking limit is reached at some current or other. If this is exceeded there is bound to be sparking at the brushes. A good dynamo, with brushes properly set, will not reach the sparking limit for the load which indicates the heating limit, while with 25 per cent. overload and readjustment of the brushes for this in the direction of rotation, the sparking limit will still not be reached.

In connection with the above it should be understood that if sparking can be avoided, a dynamo might be operated for an hour or two at a large overload and the rise in temperature of its parts be no greater than that which results from continuous operation at full load. Starting cold, it takes some time even under abnormal conditions to reach a high temperature.

60. Electric Heating.—The heating effect of current is made useful in many pieces of apparatus. For example, in electric lamps, when some part is heated to incandescence (these will be described later); or in electric furnaces of various sorts, where industrial processes are carried out by passage of current.

Another class of apparatus in which the heating effect of current is used is well illustrated by a disc stove. This is made with a top of a plate of cast iron having a smooth upper surface. Below this, but close to it, is the conductor in which heat is produced by the passage of current. In some apparatus a thin enamel is baked to the iron; then the conductor to be used (a non-oxidizing alloy, for example) is set in zig-zag form against the enamel, and another coat spread over it. Fig. 71*a* shows such a stove and in a separate view its method of construction. When it is baked fast, the heating conductor is securely fastened but insulated. By conduction the heat is passed into the cast top, while suitable means are taken to protect the heating conductor and prevent the heat developed in it from being dissipated in useless directions. A 6-in. disc stove would use about 450 watts. If it is to be used economically for heating or cooking, the vessel in use should cover the whole top and be in intimate contact with it all over. If current is left on and there is nothing to be heated the temperature may rise high enough to "burn out" the stove.

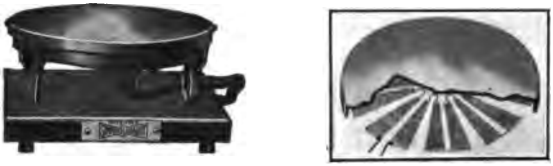


Fig. 71*a*.—Electric hotplate. Arrangement of heating wires shown in right-hand view.

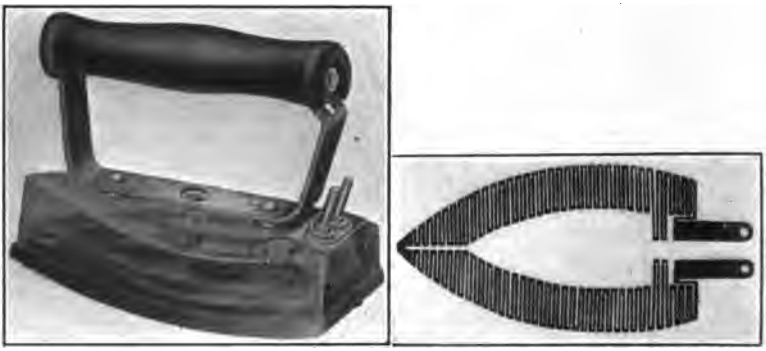


Fig. 71*b*.—Phantom view of electrically heated flat iron. Right-hand view shows construction of the heating element which is used between mica plates close to the base of the iron.

A very large amount of heating apparatus is built by using an alloy conductor which has a high resistance (perhaps 50 times the resistance of copper) and which will endure high temperature. After placing it between mica sheets for insulation, it is clamped firmly to the piece to be heated. Fig. 71*b* shows this construction by a phantom view of a well-known electric flat iron. In this case a thin sheet of the resistance material separately shown, has been cut in a punch press to a form which gives some rigidity to the unit but makes the path for current long and of high resistance. One of the difficult problems in electrical heating apparatus is to keep the heating conductor of small bulk and to so arrange it that the heat developed per square inch of heater is great enough to be satisfactory.

61. Fuses.—A fuse is a piece of metal of such size and composition as to melt when the current passing through exceeds some chosen value, and so it automatically opens the circuit. Fuses are very common safety devices used to prevent dangerous rise of temperature in a circuit in which they are included. Commonly they are made of a metal which melts or fuses at a low temperature. Lead or a lead-tin alloy is often used; sometimes an addition of bismuth is made to the alloy to reduce the fusing temperature. A satisfactory fuse should open the circuit quietly; should maintain firm contact with the circuit connections as by having hard metal ends; should have a definite current at which it will melt, not influenced by long heating; be so arranged that surrounding objects are not likely to be set on fire when it melts; be long enough so an arc will not be maintained when it melts. In the next chapter various forms of fuses are shown (see section 66). Looking at them it will be easy to see how well they meet the requirements here stated. A simple fuse wire is never a reliable current interrupter, partly because of the variable cooling effect of the terminals (due to difference in size and spacing), partly because in a warm place a fuse will melt off with much smaller current through it than in a cool place. To give an idea of the fusing current for a given size of wire it may be stated that No. 10 copper wire will melt off with about 335 amp. through it, while a lead wire of the same size melts off with about 42 amp. The copper would melt at 2000°F. and the lead at 600°F.

QUESTIONS AND PROBLEMS

1. A man pushing on the end of a vertical windlass arm exerts a force of 40 lb. He is pushing at a point 4 ft. out from the axis and

completes a round every 30 sec. After a quarter of an hour how much work has he done? How much power has he been exerting?

2. An elevator weighing 1200 lb. rises the whole height of a 330-ft. building in 3 min. How many foot-pounds of work have been done? How much horsepower has been continuously supplied to do this? What horsepower is required of a motor to drive the machinery if its efficiency is 70 per cent.?

3. A hoisting motor is lifting earth by means of a derrick to which is connected a bucket holding a cubic yard of earth. If the earth and bucket weigh 3500 lb. and only 50 per cent. of the power of the motor is available for the hoisting, what power is being produced when the load is rising steadily at 120 ft. per minute.

4. On a certain lathe a wrought-iron piece is being turned, the depth of cut being 1⁄10 in. and the feed 1⁄8 in. The diameter of the piece is 6 in. and it is making 25 r.p.m. The pressure of the tool against the metal to turn it off is 4000 lb. What horsepower must be supplied by a motor to drive the lathe if the machine has perfect efficiency? What if the efficiency is 85 per cent.?

5. A dynamo is driven by an engine. It is loaded to 800 amp. at 125 volts. How many horsepower is the engine developing? Where does the power go if there are only lights on the circuit?

6. A steam engine develops 91 hp. in the cylinder. It uses 6 hp. in its own friction. The dynamo driven by it is developing 57 kw. What is the dynamo efficiency?

7. A certain motor is developing 4 hp. when supplied with 3730 watts. What is the efficiency?

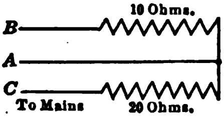
8. A street car weighs 30 tons loaded. The drawbar pull due to track resistance is 20 lb. per ton. When running 5 miles per hour what power is required to propel it? What current from a 500-volt line if the motors have 80 per cent. efficiency? What power and current at 15 miles per hour?

9. Would 20°C. be a comfortable temperature? Could a man put his hand on something which was at a temperature of 50°C. without getting burned? Turn these into Fahrenheit temperatures to help with answers.

10. How many B.t.us. are necessary to raise the temperature of a bucket of water (2 gal. at 8⅓ lb. per gallon) from 50°F. to 212°F.?

11. Two copper wires are in series in a circuit. One has a section half as big as the other. Make a comparison of the amount of heat delivered to each one. Make a rough comparison of their rise in temperature.

12. A certain electric stove is made to develop two heats by the use of a switch which changes one main connection from *A* to *B*, the other being always on *C*. The circuit is 120 volts. On which switching point is most heat produced and why?



13. A certain 100-kw. dynamo (built for 125 volts) is directly connected to an engine. The efficiency of the dynamo at full load is 92 per cent. and the loss in the engine is 7½ hp. How many horsepower does the engine receive from the steam line at full load of the dynamo? How many amperes does the dynamo supply at full load?

14. A residence watt-hour meter reads 107,630 watt-hours at the end of one month. At the end of the next month it reads 284,030 watt-hours. Only incandescent lamps have been in use giving 20 cp. at 1.25 watts per candlepower with 110 volts applied. How many lamp hours have been used? What is the bill? If burned 3 hr. each night and for 30 days, how many lamps have been burning to have such a bill? How much does it cost to burn one lamp for an hour? Price of current, 6c. per kilowatt-hour.

CHAPTER VII

DIRECT-CURRENT SYSTEMS OF DISTRIBUTION

62. Various Systems.—Current is distributed either through simple-series circuits (see Fig. 4) or simple-parallel or multiple circuits (see Figs. 5 or 6). The series distribution is with constant current and the multiple distribution at constant potential. Series circuits are used almost exclusively for lights out doors, while multiple circuits are used for all sorts of purposes. Other more complicated connections, such, for example, as a multiple-series connection of incandescent lamps on a series lighting circuit, have long since been abandoned. The only departure from simplicity is to find not infrequently two or more pieces of apparatus in series connected as one to a multiple constant-potential system, as, for example, when two 110-volt lamps in series are connected across a 220-volt system.

63. Constant-current Distribution.—In a series circuit means must be provided so that the current is fixed in amount, no matter what the number of lamps in use, while turning off one lamp must not interfere in any way with the flow of current through the others. Hence, the dynamos required to furnish current to such systems must be machines expressly designed to maintain a constant current by automatically raising their e.m.f. in proportion to any increase in resistance in the circuit as more lamps are turned on, and lowering it automatically when the resistance decreases. These dynamos are not much used to-day and each make is very special in character, so no attempt will be made to describe them here.[1] They are essentially high-voltage machines, since with a constant-current circuit of 10 amp. for only 100 kw. to be spent in lights, the terminal volts of the dynamo would be 10,000. Common values of current for series arc lighting are 6.8 amp. and 9.6 amp. On 9.6-amp. arc circuits, dynamos are not made to generate more than 6000 volts. Since the dynamos supply constant current, no short-circuits or changes in resistance can lead to large flow of current, and so no fuses are necessary in the circuit. An open circuit will put out all the lamps in the circuit. No safeguard against breaks between lamps can be provided, but each lamp is provided with a switch and a cut-out. The switch is to short-circuit the lamp and so cut off current from it, in order to turn off the lamp without opening the whole circuit. The function of the cut-out is to do the same thing automatically so a closed circuit may be maintained, even if the circuit opens within the lamp itself.[1]

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[1] See Crocker and Wheeler, "Management of Electrical Machinery," for detail.

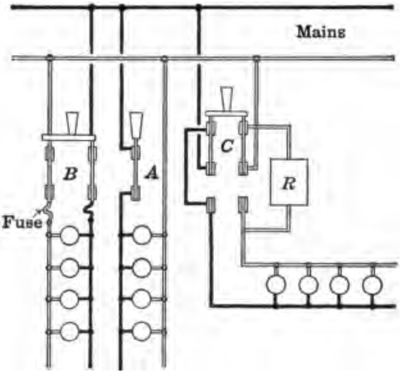

FIG. 72.

64. Constant-potential Distribution.—In this system of distribution all pieces of apparatus are receiving current in parallel. The amount of current each receives may be quite different from that received by any other, and to turn off current from any one a switch in the line to it is opened. In any practical system, current-using devices are installed on branches of the main system. Hence there are *mains*, the main wires through which current passes; and *branches*, the local and less important wires through which current flows to the current-using devices. In Fig. 72 there is shown a pair of mains, to either end of which a dynamo might be connected and three branch circuits.

Since circuit voltage is everywhere obtained between the wires of mains and branches it is usual when referring to these wires to speak of the sides of a circuit. Thus, that made solid black would be the positive side if the current flowed from the dynamo to the lamps through it, and the other side would, of course, be the negative side of the circuit. Even if each lamp were turned off and no current were flowing, the same method of designation for the sides of the circuit would be used; and if the dynamo is connected, the circuit would be said to be "live," that is, ready to supply current the minute anything were connected from one side to the other.

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[1] Explained further under description of arc lamps.

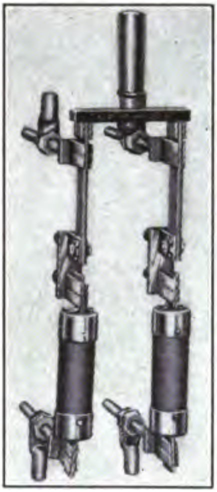

Fig. 73*A*.

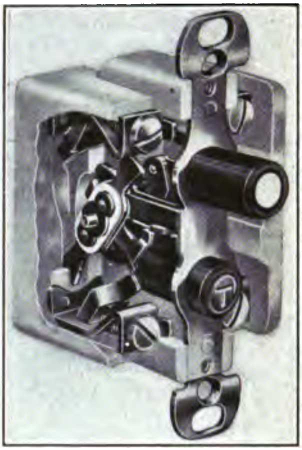

Fig. 73*B*.

65. Switches.—In Fig. 73*A*, *B*, *C*, are shown switches for controlling groups of lamps or other current-using apparatus. Knife switches are made for any current capacity and are rated by the number of square inches of contact surface provided when the blades are enclosed by the clips. A good switch will maintain very perfect contact there, the joint being "ground in" with emery and oil for good construction. They should have 1 sq. in. of contact area for every 100 amp. carried. Knife switches for less than 25 amp. are too frail to be useful. In Fig. 73*A* a double-pole, single-throw, back-con-

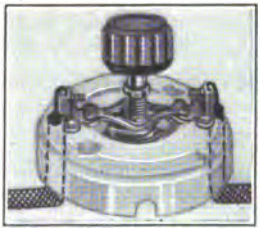

Fig. 73*C*.

nected fused knife switch is shown complete and ready for mounting on a backboard of non-conducting material. In Fig. 72 at *A* is shown a single-pole knife switch controlling one branch circuit. It is single pole because it opens only one side of the circuit. At *B* is a double-pole switch, and at *C* a double-pole, double-throw knife switch arranged so that in the position shown the rheostat *R* is in series with the lamps, while if thrown the other way the lamps are connected directly across the circuit.

Snap and push switches are installed where only moderate amounts of current are to be carried and persons unfamiliar with electric circuits are likely to manipulate them. Usually they do not carry more than 10 amp. In Fig. 73*B* a push switch is shown without its flush plate and with the porcelain box in which it is mounted partly broken away to show the mechanism and how one side of the circuit is closed when the white button is depressed. At *C* is a single-pole snap switch, shown without its cover in the closed position. Revolving the knob winds up a spring and causes the connecting piece to suddenly swing through 90 degrees. Push and snap switches are always made so that the circuit can only be opened by a quick break action. In Fig. 73 the switches are shown without reference to their relative scale. They are simply made of a convenient size to show their parts clearly.

66. Fuses.—In a constant-potential circuit the current is regulated by the resistances connected across the circuit. Thus, if a single lamp takes 1 amp., when another similar lamp is turned on 2 amp. are coming over the line. If some low-resistance apparatus were connected, a very large current might flow, an amount large enough to heat the conducting wires to a dangerous temperature or burn out the apparatus itself. If the sides of the circuit were to get together a "short-circuit" would be formed, and then the generating machinery would be endangered by the load put upon it. Fuses are, therefore, installed at every point where a branch circuit meets a main, or whenever the size of conducting wires is changed. Fuses are mounted on fuse blocks or cut-outs usually made of porcelain with brass or copper conducting pieces mounted on them. In Fig. 74 is shown a double pole single branch plug cut-out. Such a device is placed at a point along a line where a branch is to be connected. The wires *A* and *B* represent the mains; wires *C* and *D*, the branch circuit. The fuse plug shown in Fig. 75 has a porcelain body into which is secured a brass contact button at the bottom and around which is spun the formed brass thread shown. The lead-wire fuse runs vertically through this porcelain body, being fastened at one end to the contact button and at the other to the top of the threaded piece. Such plug fuses are made for various currents up to 30 amp. and each

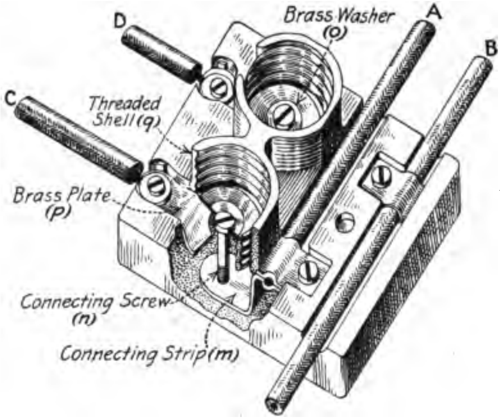

Fig. 74.

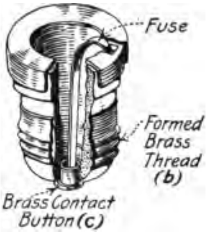

Fig. 75.

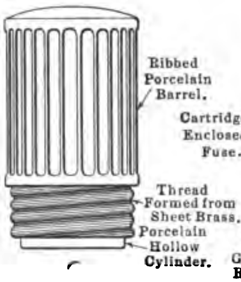

Fig. 76.

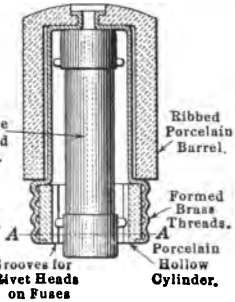

Fig. 77.

is marked with approximately 80 per cent. of the current at which it will melt off. When such a plug is screwed into the cut-out, connection is established from one main to a branch wire. From wire *A* we pass through strip *m* and screw *n* to contact button *c* of the fuse plug. Thence up through the fuse to thread *b* to shell *q* to brass plate *p* and so to wire *C*. Brass washer *o* holds a mica disc in place, which insulates it and screw *n* from the plate *p*.

More expensive fuses are much used to-day. Fig. 76 shows an outside view of an enclosed fuse plug to fit the same cut-out as that just described. Fig. 77 shows a section of it and shows the cartridge or enclosed fuse proper which it contains and which can be renewed at will. The figure shows with sufficient clearness how the connections through the fuse are completed if it is understood that a brass cap covers each end of the cartridge and the fuse reaches from one of these caps to the other. Another way of mounting a cartridge fuse is shown in Fig. 78. Enclosed fuses are constructed in such a way that when the fuse melts off, even if the opening of the circuit is accompanied with considerable arcing, nothing can be set on fire. Inside a fiber tube is a wire or strip of lead (or zinc or other metal) soldered to the brass end pieces. Except for a small space near the center of the tube the space is filled with an insulating powder, such as lime or talc. Under excessive heat this powder fluxes and both by absorption of heat and smothering the arc the circuit is opened quietly and safely. The filling material must absorb no moisture. If it did, when the fuse melts steam would form and the cartridge explode. All such fuses are equipped with some sort of tell-tale device so that upon external inspection one can tell whether or not the fuse has blown.

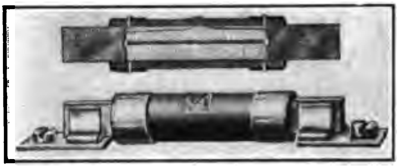

Fig. 78.

67. E.m.f. for Constant-potential Circuits.—A great majority of the circuits used for the distribution of current indoors, have a difference of potential of 110 to 125 volts maintained between the two sides. This is therefore the terminal P.D. of the dynamo connected to them. The figure established for a given system is kept constant on it. 110 volts is very widely in use, but no special advantage attaches to this figure. This e.m.f. is not dangerous to any person and is well adapted to lights and smaller power uses. 220 to 250 volts are used for power purposes, especially in industrial plants. Sometimes a still higher e.m.f. is used. Thus, for street railways, which use the constant-potential system of distribution partly because the cars must receive current in parallel, from 500 to 700 volts are used. The advantage of high voltage is that the current is reduced for the same amount of power transmitted and so the size of wire to carry the current can also be reduced.

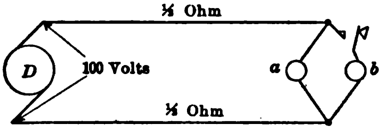

Fig. 79.

In order to have the current through any piece of apparatus on a constant-potential system quite independent of the current in any other thing, the volts at its terminals must stay constant. In order that this may be true not only must the dynamo be of the right sort (see next section), but the wires supplying current would have to be without resistance. Thus (Fig. 79), if lamp *a* is turned on and using 2 amp., there are 98 volts at its terminals, since 1 volt is lost in driving the current through each of the leads. If, when the circuit *b* is closed, 2 amp. flow, only 96 volts are at the terminals of *a* and so the current through it is some 2 per cent. less than before. The lower the resistance of the mains and branches the less will this defect show. All practical systems have the distributing lines chosen so their resistance is sufficiently low as to be nearly negligible. This matter is further explained in Chap. XVIII. The important thing to recognize at this point is the importance of low-resistance distributing lines as an aid to constant potential at the receiving devices.

68. Dynamos for Constant-potential Systems.—The thing of fundamental importance in a constant-potential system is the dynamo. A machine must be available which can supply a constant potential at its terminals.

Every dynamo has its peculiarities and individualities which may be called its characteristics. Dynamo characteristics admit of examination by the aid of curves derived from experimental data. It is common to arrange characteristics with volts plotted vertically and amperes horizontally. In the external characteristics the terminal volts are plotted for every current flowing through the external circuit, the dynamo being operated at constant speed. Dynamos of a given type have characteristics similar to each other. The only types of dynamos which have external characteristics which make them at all available for constant-potential systems are shunt dynamos and compound dynamos.

69. The Shunt Dynamo.—In Fig. 80 the curve *A* shows a typical characteristic for a shunt dynamo. If the field rheostat of the dynamo is not touched, as the current supplied by the dynamo is increased, the terminal volts fall, only a little at first, but afterward more rapidly until the point *c* along the curve is reached. For the dynamo considered the terminal volts are 120 at no load and only 100 when 50 amp flow. The remaining part of the curve to *d* is of no practical interest except to show that if a shunt dynamo is short-circuited, it will not come to harm. No more current then flows than indicated by the distance *od*, namely 12 amp., for since the armature is short-circuited, no current flows in the field and the only e.m.f. generated is that due to residual magnetism. The drop in terminal volts with increasing current shown by the curve is partly due to resistance in the armature which causes more drop there, and this in turn means less volts to send current through the field winding.

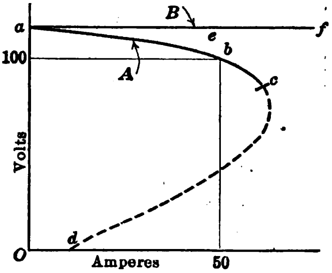

Fig. 80.

It is also partly because the increased current through the armature produces an increasing magnetizing effect which reacts on the main field, weakening it. Should the dynamo decrease speed due to belt slip or decrease of engine speed or both, instead of reaching 100 volts at 50 amp. (point *b* on curve) there would have been still less volts for this current.

A dynamo designed so that the drop along the line *abc* is slight would be nearly a constant-potential machine. If the load changes gradually, any defects in the dynamo due to the inherent nature of the external characteristics can be compensated by hand manipulation of the field rheostat, the man in charge cutting out resistance so as to allow more exciting current to flow and thereby raise the voltage when he sees by the voltmeter a tendency for it to fall. This is the method used in practice. Shunt dynamos are often used in large central stations which supply current for lighting.

70. The Compound Dynamo.—As explained in section 40, a compound-wound dynamo has both shunt and series magnet windings on its field cores. As the current to the external circuit increases, the magnetizing effect of the series field increases with it and this, supplementing the effect of the shunt field, increases the flux and the generated e.m.f. as may be desired. If this increase is just enough to balance the drop which would be found in a shunt dynamo, an external characteristic shown by the line *B*, Fig. 80, would be found. This shows an exactly constant terminal voltage as the current increases. The amount of this compounding effect of the series winding can be regulated so that the external characteristic may turn out to be a horizontal line, one which rises, or one which drops. A compound dynamo which automatically keeps the voltage constant so that the external characteristic is a horizontal line is said to be compounded flat. One for which the characteristic is inclined upward is said to be over-compounded; one for which the line is inclined downward is said to be under-compounded. An adjustment of the amount of compounding effect of a given series winding can be made by putting a shunt across the terminals of the series field, according to the plan shown in Fig. 81. The series winding of a four-pole dynamo is shown, marked *FF*, and the shunt is marked *S*. The lower the resistance of this shunt the less the compounding effect

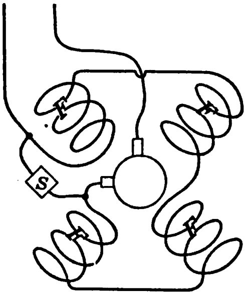

Fig. 81.

of the series winding. For most machines the terminal volts rise slightly as current increases to half load (from *a* to *e*) and they drop again as it further increases to full load (at *f*). Compound dynamos are used for isolated plants where the regulation must be nearly automatic, and for electric railways where the load fluctuates suddenly and over large ranges and in spite of this the voltage must be maintained nearly constant.

On all constant-potential distribution systems the volts are so nearly fixed that in common usage "the load" and the current demand are used interchangeably. If then twice as many lamps were turned on, or if an ammeter in the line read twice as much as before, we would say that the load had doubled.

71. Providing for Large Current Demand.—Every dynamo has a certain kilowatt capacity determined by its heating and sparking limits (see section 59). Hence on a constant-potential system of any size the current demand may easily become larger than that which can be supplied by any one dynamo. When this condition arises, another dynamo is put in parallel with the first one and when their combined capacity is reached, a third machine is put in parallel with the two which are in operation. In this way not only is a means provided for handling loads of any size, but it is possible to take any machine out of service or to substitute another without the change in the source of current being perceptible to the user. The theory which explains how this can be done and why the load may be shared as desired among the machines operating in parallel is given in Chap. IX, section 105. Any number of dynamos may be operated in parallel if of the same sort. For the sake of simplicity in managing the system, it is desirable to limit the number so operating to two or three.

72. Shunt Dynamos in Parallel.—In Fig. 82 is shown a diagram for two-shunt dynamos arranged so either or both of them may supply current to the load of lamps. S_1 and S_2 are double-pole knife switches which control the supply of current to the load. M_1 and M_2 are double-pole knife switches to control the connection of the dynamos to the load. Connections between dynamos and load are by way of bars (marked $+B$ and $-B$) which are called busbars. Each dynamo is provided with an ammeter and a voltmeter. The ammeter tells the amount of current supplied by a given dynamo at any time. The voltmeters give the means of keeping constant potential at the dynamo terminals or at the busbars and are used in connection with the operation of putting machines in parallel as will be presently described. It may be noted that fuses *fff*, are provided in the lines leaving the busbars as well as in those supplying current to them, and that switch blades and fuses are so placed that when switches are open, the blades will be "dead"[1] and fuses can be renewed without risk of a shock or producing a short-circuit.

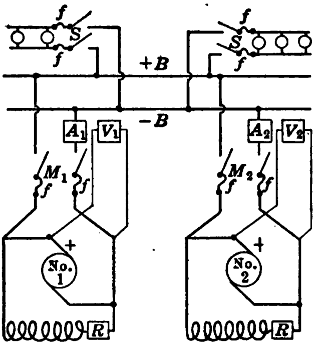

FIG. 82.

The process of putting a dynamo in parallel with one already in operation is by the following method. Suppose dynamo No. 1 is connected to the busbars and operating under load. It is desired to connect No. 2 in parallel with it. When No. 2 is running at full speed, by adjusting its field rheostat *R* bring its voltmeter to the same reading or a slightly higher reading than that shown on the voltmeter of No. 1. Be sure that when the switches close, the + terminal of the incoming machine, No. 2, will be connected with the positive busbar. Close the main switch.

When they are in parallel, adjustment of the field current by manipulation of the field rheostats distributes the load between the machines as desired. The dynamo whose field is strengthened has the load which it carries increased, while that of the other machine is correspondingly decreased. When once in parallel, dynamos of the same type will keep the same distribution of current between them no matter how the total demand varies.

73. Compound Dynamos in Parallel.—Fig. 83 shows by diagram the connections for operating compound dynamos in parallel. A comparison of Figs. 82 and 83 will show many points of similarity. There is, however, a third busbar marked *E*, known as the equalizer, which, when the dynamo switches are closed, connects the + brush of one with the + brush of the other. The main dynamo switches are triple-pole switches arranged usually so that all three blades close at the same instant, while fuses are provided in + and − leads but not in equalizer connections. The equalizer is always a conductor of very low resistance, its purpose being to put the series fields of the different machines in parallel so that, no matter what current flows through a given armature, the division of current through the series fields is always the same. The series fields must, for all the dynamos which are to be operated in parallel, be connected to the brush having the same polarity.

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[1] That is, entirely clear of connection with any source of current.

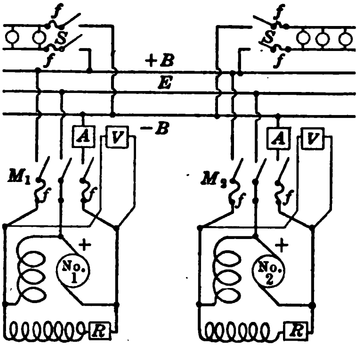
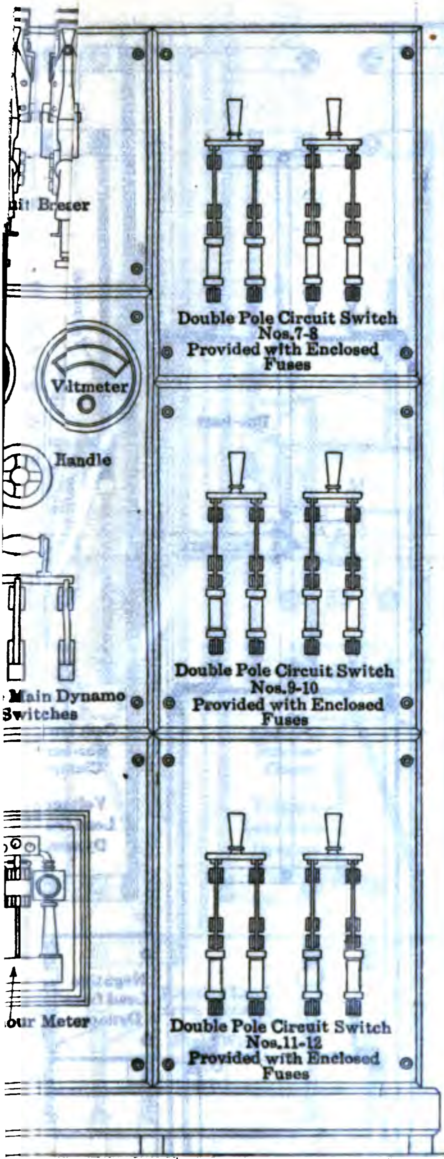


Fig. 83.

The process of putting compound dynamos in parallel is precisely the same as that described for shunt dynamos in the last section, if the dynamos are "compounded flat" and are connected by triple-pole switches. Dynamos which are over-compounded are very difficult to put in parallel, unless they have three single-pole switches for connecting them as they often do in railway work. A certain sequence must then be observed in making the connections. The plan is first to close the equalizer switch; next the one at the positive terminal of the incoming machine. This puts the series fields in parallel. Next adjust voltage of the incoming machine to a value 1 or 2 per cent. above that of the busbars and then close the last of the single-pole switches. Proceed to divide the load by manipulating the field rheostats.

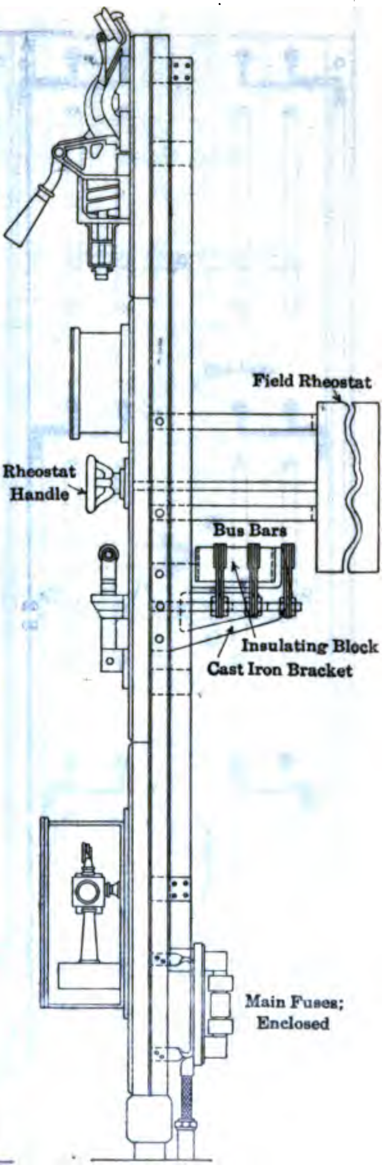
In the diagrams no provision has been made for a switch in the shunt-field circuit of the dynamos. It is a very rare thing to have such a switch installed. Each dynamo is supposed to be "self-exciting" immediately upon being started up, and when a dynamo is shut down, the field current may die out as the dynamo slows and stops. Furthermore, the shunt field always has a great many turns in its magnet winding through which the large flux of the magnetic circuit goes. When the current stops the flux stops too; and so if a switch in this circuit were opened, a large and sudden change in flux occurs through every one of these turns. A tremendous e.m.f. may thus be generated in the field coils, enough to break down the insulation (see also section 106). If such a switch must be installed, some arrangement must be provided so that it cannot be suddenly opened.

74. Switchboards and Switchboard Connections.—The diagrams in the preceding sections to show how dynamos are connected in parallel fail to give any real idea of the connections as they are made in practice. Dynamos are never connected directly to the circuits they are to serve. The switches, busbars, and necessary measuring instruments are always mounted on a switchboard where they are grouped in a convenient way. The various circuits of the system, which have been planned so that a convenient and useful control over the use of current may be obtained, begin at switches mounted on the switchboard where an attendant has them in charge. Cables from the dynamos end at the switchboard where control apparatus is placed so that it is easy to regulate their output and impossible to make any mistake about which apparatus belongs to a particular machine. A very common plan is to arrange things in panels; that is, in narrow sections, with all the apparatus from top to bottom of such a subdivision or panel belonging to a particular machine or service. Fig. 84 shows a drawing of a switchboard as it would be arranged in good practice. There are four panels. The central ones are for two compound dynamos; the outer ones are load panels; that is, they contain the switches through which the load is distributed. In the left-hand or front view the left-hand panel contains switches to control a motor load, while the right-hand panel has on it the switches for the lighting load. The drawing shows front and rear views and also a section through a generator panel. If properly folded, it is possible to look at the face and then at the back view, carrying the connections through and noting how the construction work is managed and how the connections are made. The board shown may be of either slate or marble. If of marble,



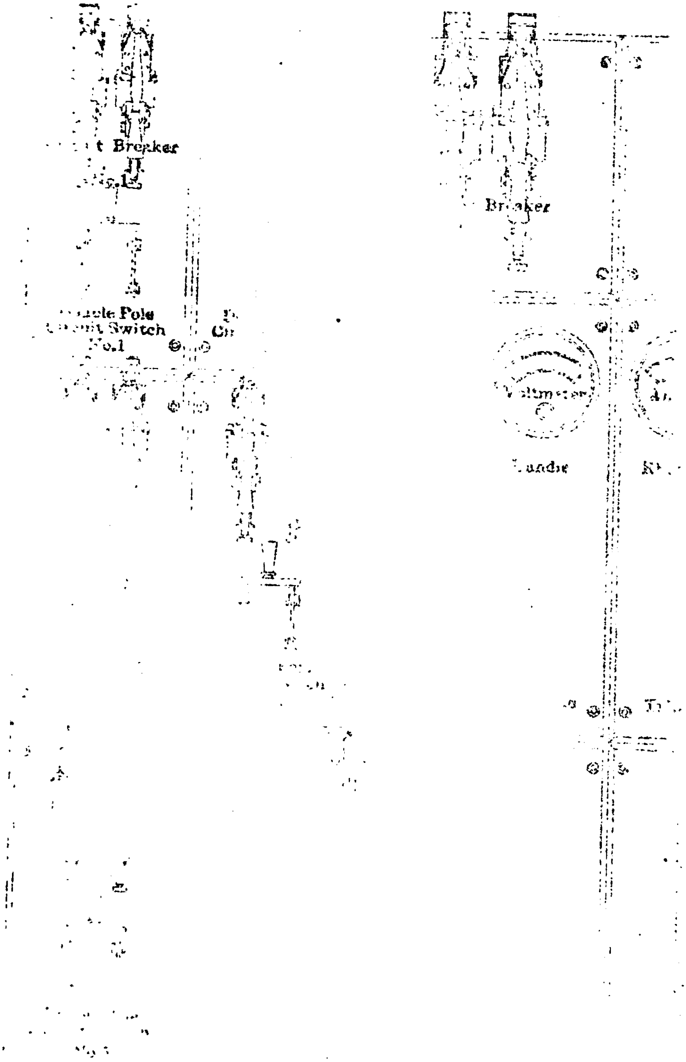
it Breaker
Double Pole Circuit Switch Nos.7-8 Provided with Enclosed Fuses
Vltmeter
Handle
Double Pole Circuit Switch Nos.9-10 Provided with Enclosed Fuses
Main Dynamo Switches
Double Pole Circuit Switch Nos.11-12 Provided with Enclosed Fuses
our Meter

Dynamo No.2



SECTION AT A DYNAMO PANEL

stant potential dynamos and distributing circuits.


t Breaker
II
Fig.1
Single Pole
Circuit Switch
No.1
Ci
Breaker
Voltmeter
Landie

it might be 2 in. thick, while slate, which is stronger but a poorer insulator, might be 1½ in. thick. These slabs of insulating material are mounted on an angle and tee iron framework, the whole thing being mounted at a suitable distance from the wall by pipe lengths ending in suitable fasteners.

Switches are mounted directly on the board by means of studs and thin nuts, the studs projecting so they may be clamped on the back to bar connections or lugs into which cable ends are soldered. The busbars of rolled copper bar marked by the proper name on the drawing, are supported on cast-iron brackets which are bolted to the vertical tee irons. On the brackets are mounted insulating blocks of slate or porcelain on which the copper bars rest. The busbars are made up of more than one bar each (see section or end view), in order to make it easy to secure large area of contact at points where other bars are clamped to them, and to facilitate bending. Cast-iron clamping pieces are shown marked "busbar clamps."

On the generator panels at the top and on the motor-control panel at the left, circuit-breakers are mounted. Circuit-breakers are magnetically operated switches arranged so that when the current exceeds a value for which they are set, a catch is released and a spring opens the circuit. A description is reserved for the next section.

In addition to matters already noted, the reader should look carefully over Fig. 84 to see the height of the board; the disposition of apparatus on it, particularly on the dynamo panels; the method used for clamping the busbars to distributing bars; and should follow the route of the current as it is brought to the board from the dynamos and delivered again through the distributing circuits.

The arrangement of the dynamo panels is a good one. The instruments and main switch are directly before the operator at a convenient height, while the rheostat can be manipulated while watching the instruments. The rheostats are shown only in the section or side view. In the rear view they are omitted so the various connections can be better seen. Their location is indicated by a dotted circle. The circuit-breaker needs no attention until it opens, and then an upward reach and downward pull (after the main switch has been opened) close it. The flash across its contacts as it opens is at the top of the board where it can harm nothing.

There are four wires from each dynamo to the switchboard—positive, negative, and equalizer (usually all of equal size) and the field wire. The positive dynamo lead (*F*) ends on a main fuse

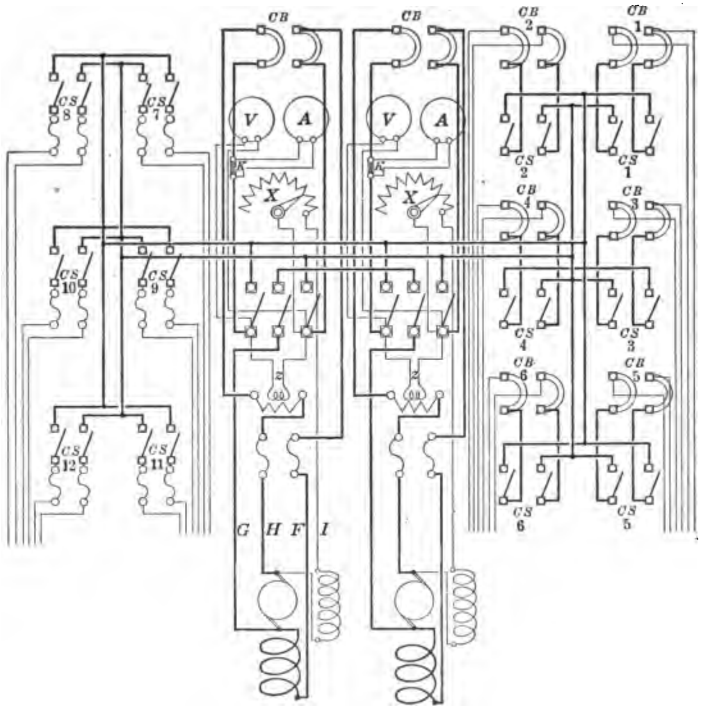


Fig. 85.

board. After passing the fuse it is carried by a vertical bar to the top of the switchboard through the circuit-breaker and then back to a stud on the main switch. The equalizer *G* is carried directly to a stud on the main switch. The negative lead goes to the fuse board, then on through fuse, watt-hour meter, circuit-breaker, and ammeter shunt (*K*) to the third stud on the main switch. The field wire (I) is connected at the board in agreement with the diagram of Fig. 85, which should be consulted and carefully compared with the switchboard drawing. The connections are such that the rheostat and voltmeter are connected behind, that is, on the dynamo side of all switches.

The three busbars are mounted directly behind one another (see rear view). The equalizer is behind the others reaching from L to M. The positive and negative fuses extend toward the right end at W in two vertical bars, one placed behind the other. At O two cross-bars, one 3 in. behind the other, are bolted on. The one farthest from the board extends from P to Q. The other, close to the board, reaches from R to S. The way in which the positive or negative bus is continued to any particular switch stud will be sufficiently clear if it is understood that the drawing shows the same sort of connections as those just described for every one of the circuit connections.

It is always difficult to plan a switchboard so a nice arrangement of connections to the distributing circuits is secured. It is assumed that in this case they are to be carried to conduits below the floor, and they are shown on the switchboard drawing, although it is very unusual to do so. The cables, beyond their connection to lugs at the switches, are encased in a reinforcing insulation of circular loom conduit to the point where they enter the iron conduits. In the drawing, fastenings to hold conduits to the angle-iron frame are not shown.

It will be noted that the lighting circuits are fused with enclosed fuses mounted on the face of the board, while the motor circuits have circuit-breakers and no fuses. This is done because motor circuits are very apt to have occasional overload currents in them, while it is an extraordinary condition which gives a lighting circuit an overload. An objection to enclosed fuses on the face of the board is found in the fact that it is hard to so arrange them that the switch can be opened wide, their height above the board causing interference with the blade when it is swung back.

75. Circuit-breakers.—A circuit-breaker, as mentioned in the last section, is an automatic switch which opens magnetically. Circuit-breakers are used in place of fuses, where the expense is not prohibitory, because their operation is much more certain and rapid than fuses; while a good one will open a circuit indefinitely without requiring renewals or repairs. Fig. 86 shows a good circuit-breaker of a well-known type.[1] Part of the framework on the side toward the reader has been cut away in order more clearly to show the operating parts. The switch proper consists of a laminated spring copper member (16) which bridges two contact blocks (98 and 50*B*). Between blocks 50 and 50*B* and connecting them is a magnet coil around core 59. Current is brought in and taken out through studs connected on the back to

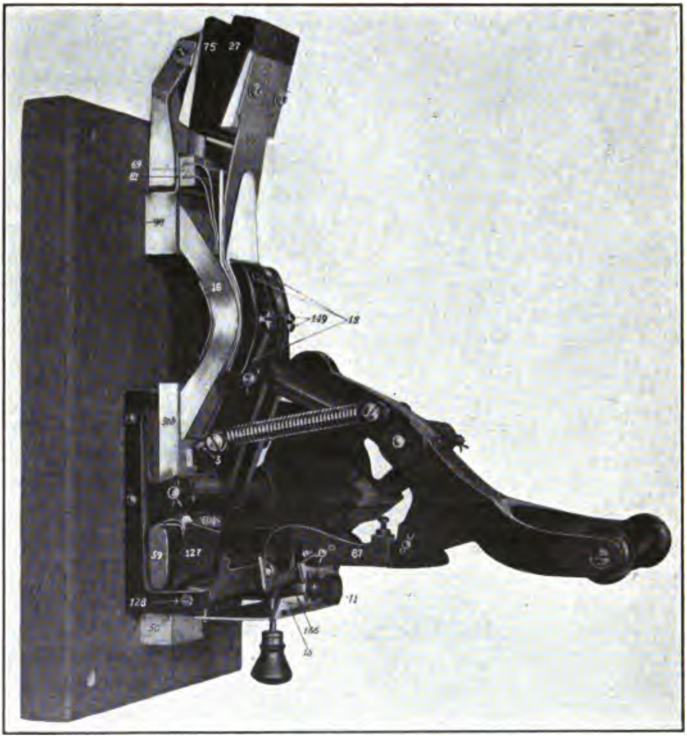


FIG. 86.

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[1] I-T-E Laminated Circuit-breaker made by the Cutter Company, Philadelphia.

pieces 50 and 98. An abnormal current in the coil causes the armature (127) to move toward it and as it moves to strike the trigger (87); on releasing which the switch, under the pull of the springs, opens suddenly. There is an adjustable stop (166) against which the armature (127) normally rests. This stop may be placed at various points along a scale marked in amperes, thus determining the exact position of the armature and so of the current at which the breaker will trip. A knob projecting at the bottom of the breaker is to make it possible to trip by hand at any time: the large handle at the right is to close the switch and reset the automatic trip.

When the switch opens, the laminated member 16 first leaves the block 98; but a good current path is still provided from 50*B* through an auxiliary block 3; a spring copper piece 30, to block 69, and thence through piece 81 to block 98. Later 69 leaves 81 but there is still a path from 3 up through the carbon blocks 27, 75 and down to 98. Thus there is no chance of burning and marring the real switch contracts, while the circuit is finally broken on carbon blocks which are designed so this will not harm them.

Sometimes circuit-breakers are provided with a magnetic blow-out which disrupts an arc which forms on the parting of the contacts. The principle is described later in section 97.

76. Switchboard Instruments.—It is not safe to operate dynamos unless they are supplied with instruments arranged so that the current output, and the terminal volts are measured. Such instruments have many forms; a type much used being here described (see Fig. 89). The indication of such an instrument is dependent on the fundamental fact that a conductor carrying current when placed in a magnetic field experiences a mechanical force. If, in Fig. 87, a current were flowing in a conductor in the direction marked beside it, it being placed in a magnetic field having the direction shown, the wire will experience a force to move it downward. The amount of force varies with the amount of current when the magnetic field has fixed strength.

Fig. 88 shows this fact put into application in an instrument, the working parts only being shown. A permanent magnet in horseshoe form, with poles marked *MM*, is arranged with iron pole pieces and a soft iron cylinder in such a way that a narrow gap space of even width is provided between the pole pieces and the cylinder. The bridging piece which supports the cylinder is of brass. A rectangular coil of many turns of fine wire swings in this gap space, supported in jeweled bearings. The jewels are mounted in the bridging pieces at *D*. The pointer *B* and coil *C* are rigidly fastened together; coiled springs, one above and one below the coil, hold the pointer to the zero position and serve as the means of getting current into it and out again. Should current flow in the coil, up in the wires on one side and down on the other, there exists a mechanical force to rotate the coil which is opposed by the springs. Thus instrument indications are secured.

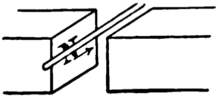

FIG. 87.

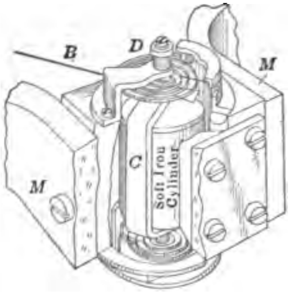

FIG. 88.

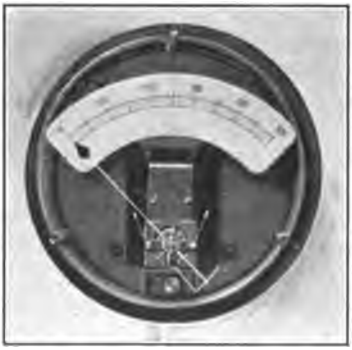

FIG. 89.

Fig. 89 shows an instrument complete except for its cover (Weston Electrical Instrument Company's make). It is easy to see that this has the same mechanism as that just described.

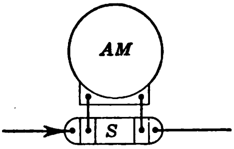

Fig. 90.

A voltmeter is such an instrument made with high enough resistance so that only a very small current flows in the coil. If 50 volts applied sends a small current which exerts a certain force to move the pointer along the scale, 100 volts applied would send twice the current and so exert twice the force to move it. The instrument then has a scale marked in volts, the current through it varying with the volts applied.

Large currents cannot be carried through the delicate springs and light coil; hence, for ammeter uses an arrangement must be made so that only a small but definite proportion of the current to be measured flows through the instrument itself. Connections would be made as shown by Fig. 90. The resistance strip marked *S* is called the shunt. Through it a very large percentage of the main current flows. Such shunts have been already shown on the switchboard drawing inserted in place in the busbars. Fig. 91

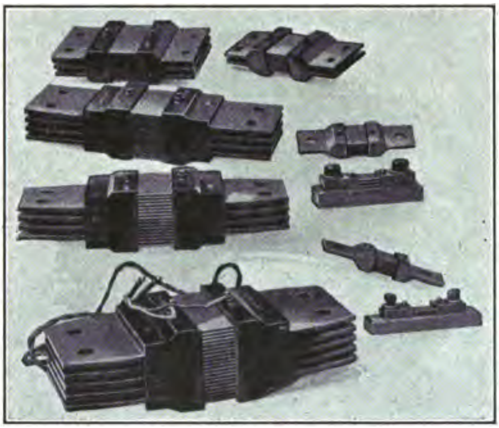

Fig. 91.

shows a collection of them as supplied by the maker, the larger ones being designed to carry the larger currents. On one, the leads which connect the instrument are shown connected.

77. A Constant-potential Network.—In a distributing system of any size, and particularly a central station system for lighting, a network is often formed. This is made of a set of distributing conductors (see Fig. 92) running along the streets and cross-connected to each other at each intersection (*A* to *I*). From them the customers are supplied through service connections (*J* to *V* inclusive). The current supply from the central station is delivered to the network through a number of feeders, one of which is shown ending at the intersection *E*. The feeders start from one, or more than one, central station; and end at different selected points of the network. Oftentimes voltmeter connections are brought back to the station from the feeding points so the volts there can be read at the switchboard.

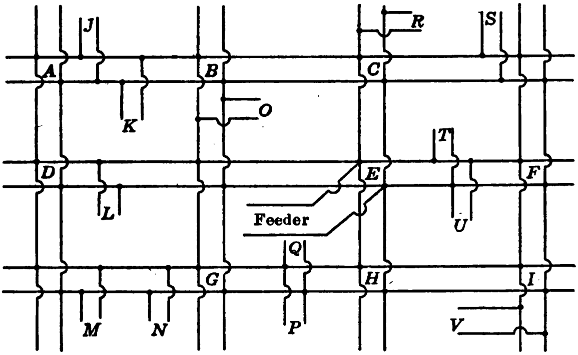

Fig. 92.

The resistance of the mains is kept very low so that without regard to the amount of current flowing in the network or the places where heaviest demand exists, the customers will all have constant potential within narrow limits. Even if the feeders have some little resistance, constant potential can be assured at the network by the aid of voltmeters connected at the point where the feeders enter the network. Shunt dynamos often supply current to the feeders.

Should a short-circuit occur on the network serious trouble will result, unless the fuses open on each side of the place where the trouble has occurred.

78. The Three-wire System.—The Edison three-wire system is a system of distribution which has long been in use for distributing current, mainly over central station mains, to customers to supply them with light and power. In it three wires are required for the distribution, the connection being as shown in Fig. 93. The mains are known as positive, neutral, and negative. They are marked on the figure. The lamp load is divided as evenly as possible between the two sides of the system so that very little current flows in the neutral. When the same number of lamps is on each side of the system it is said to be "balanced" and no current at all flows over the neutral. Motors, except in the smallest sizes, are connected between positive and negative. A common e.m.f. for each side of the system is 110 volts, 220 volts being therefore that between positive and negative. The dynamos are connected as shown in the figure. When the demand for current is greater than two dynamos can supply, more are put in parallel with *A*, or *B*, or both, as desired. Shunt dynamos are commonly used.

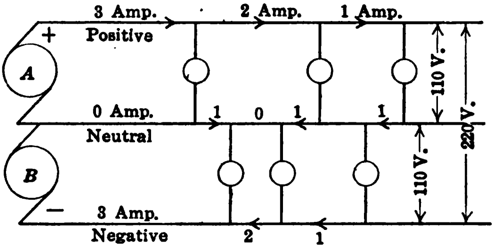

Fig. 93.

When a three-wire system is unbalanced some current flows over the neutral back to the dynamos. The amount is the difference between that flowing out in the positive and back in the negative. If the large current demand is on the positive side, the current flows toward the dynamos in the neutral.

The reason for the use of this system is to be found in the fact that a considerable saving in the cost of the distributing system can be made; much smaller conductors being required than when a two-wire system is installed. Nearly all large installations for lighting or for lighting and power are three-wire systems.

City distribution systems are usually networks similar to that already described for a two-wire system. Commonly such networks are run in Edison tubes. They are 20-ft. iron pipes in which three bare conductors of equal size have been placed and insulated from each other and the pipe by a solid compound. The neutral is generally next the curb, the positive at the top, and the negative at the bottom of a tube. Joints between tube ends are made by a coupling-box of cast iron in which flexible connectors join the projecting ends to each other. The box is then filled with compound. Service connnections are taken out at these same coupling boxes. Fig. 94 shows a coupling box for a service connection with short conduit pieces in place, and wires properly connected. They may be either two-wire, or three-wire according to circumstances. Feeders are generally lead covered cables brought out from the central station to junction boxes, different from Fig. 94, through creosoted wood or terra cotta conduits.

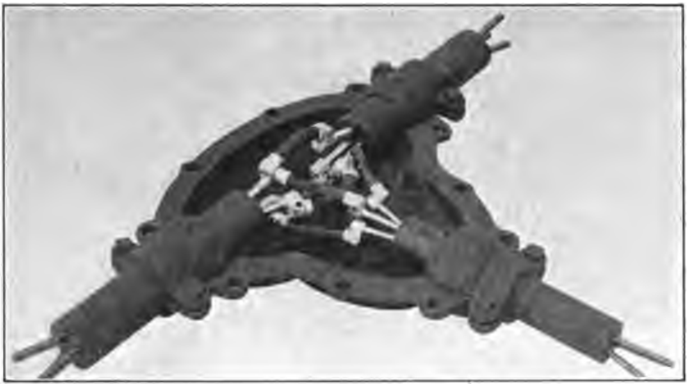

Fig. 94.

79. Distribution to Railways.—Railway distribution systems are operated at constant potential but the arrangements for distributing current are so different from those used for lighting and industrial power that a separate description is necessary.

A common e.m.f. for distribution is some fixed value between 500 and 700 volts. Fig. 95 shows an elementary diagram of a distribution arrangement. The current comes from the trolley wire and returns through the track. Hence all the cars receive current in parallel. The path in a given car is down the trolley pole, along an insulated wire past a lighting arrester, through fuse and circuit-breaker to car motors. From them a cable connects to the motor frame and thence the current flows through truck, axles, wheels to the track. More detail regarding the path through the motors is found in Chap. VIII.

The amount of current required by a car, as well as its location on the system is quite variable. The exposed bare trolley wire also makes the chance for faults and short-circuits so great that the distribution system is managed in separate parts, the trolley wire being broken into sections as shown in the diagram, each section, *A*, *B*, or *C*, being served from the central station over a separate feeder as Fig. 95 shows. Each feeder is tapped to the trolley line at intervals of a few poles so that the feeder becomes a supplementary supply line all along the trolley wire. To make this all seem more real, consult Fig. 96 in which a tap from a feeder along the pole line is shown taking the place of part of an insulated span wire, while the car has the same relation to the current supply as shown at *C* of Fig. 95. In Fig. 97 the upper part shows trolley wires for a double track road as they are supported at one span wire. A section insulator is shown inserted at this point in the line nearest the reader.

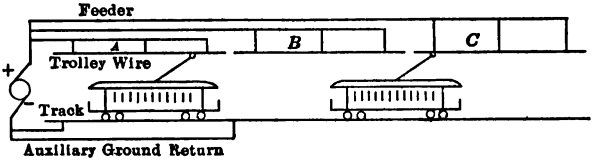

Fig. 95.

The track makes a good return path when bonded around the joints, for although of iron it has large total cross-section. In the lower part of Fig. 97 bonds on rail joints are shown. When large currents must flow through the track return auxiliary ground return lines, of bare copper cable, are installed.

Feeders may run on pole lines overhead; or be carried in underground conduits, the trolley wire taps then being brought out through the interior of iron poles and connected as shown in the overhead construction of Fig. 96. On heavy interurban or elevated lines a third rail is used instead of the trolley wire. A shoe or shoes on the car then sliding on the third rail will take current into the apparatus on the car.

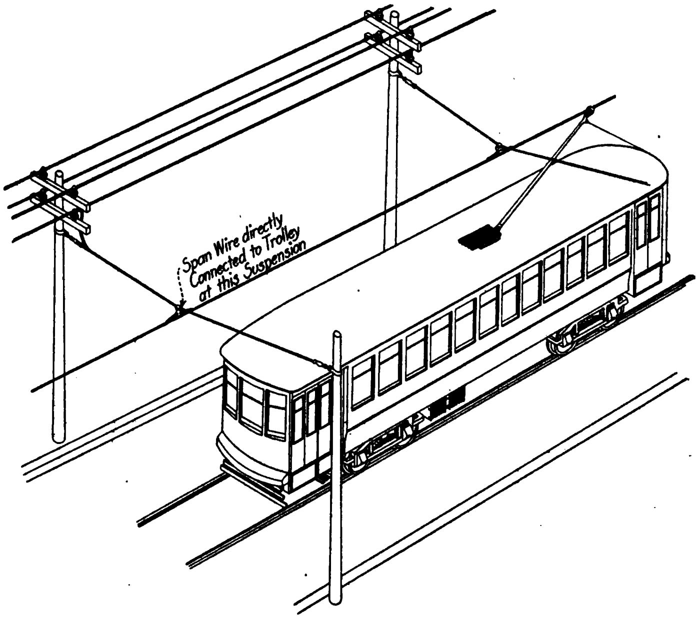

Fig. 96.

On any car there are not only the circuits through the propelling motors, but several others for lights, heaters, air-brake motor, etc. Current after flowing down the trolley pole passes to any or all of these which are connected through fuses and controlling switches in parallel with each other. On a 500-volt system the ten lights on a car are arranged in two series of five each (the lamps being for 100 volts each); while the four heaters may be connected in series across the line or by a special switch thrown into various other circuit combinations.

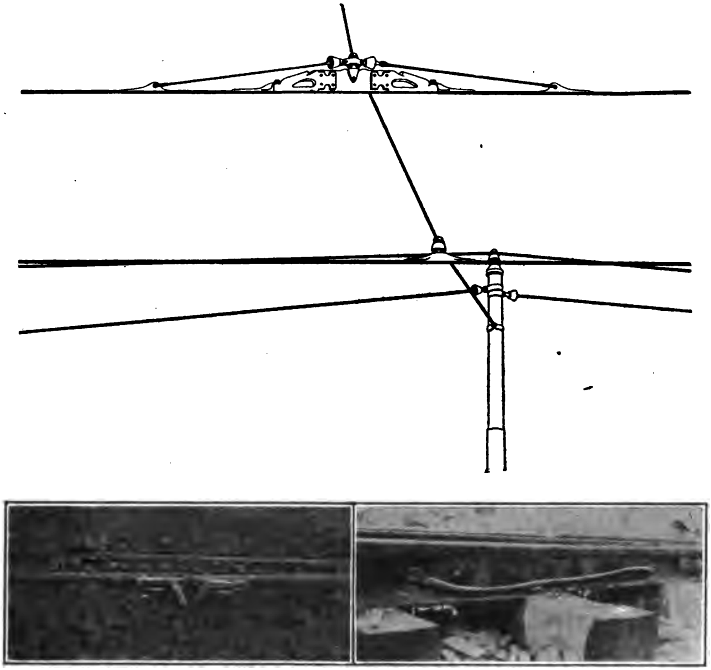

Fig. 97.

80. Switchboard Arrangements for Railroads.—For railway work things are commonly arranged so that the equalizer connection of the dynamos and the negative or grounded side of the system do not appear at the switchboard at all. Such a board is shown in Fig. 98. At the right-hand end of the board is a long line of feeder switches—eighteen of them. Further to the left after passing a couple of special panels, the dynamo switches and instruments are found. A very common arrangement is to have only one single-pole switch per dynamo at the switchboard. At each dynamo there is a pedestal and tablet on which are mounted single-pole knife switches. One connects the proper point to the equalizer and the other the negative machine terminal to a bar which is mounted against a wall in the basement of the station, it in turn being connected directly to track and ground. The diagram of Fig. 99 shows how such a switchboard is arranged (compare Fig. 98). Single-pole main switches, ammeters, circuit-breakers and a voltmeter are the only necessary instruments and apparatus. The positive bus runs along the top of the board and behind each panel a branch turns down through a circuit-breaker, ammeter, a feeder switch, and then continues in underground cable to a certain portion of the system as A, or B, or C of Fig. 95.

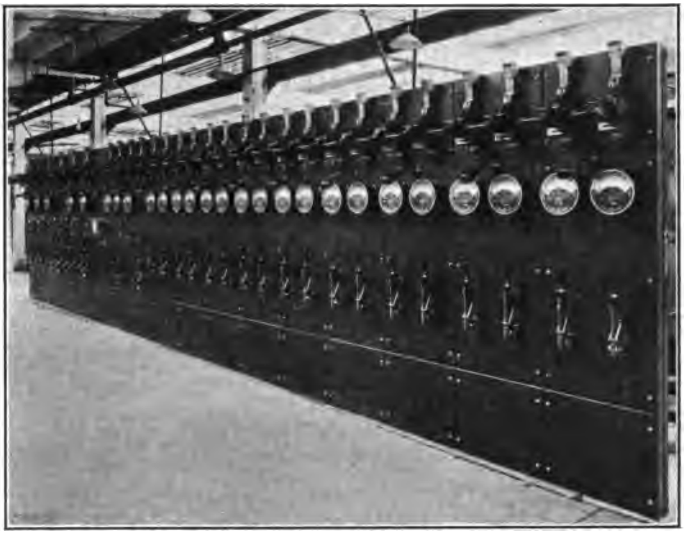

Fig. 98.

Circuit-breakers are very important adjuncts of the feeder system of a railway. The current over any feeder line is very fluctuating and when several cars start at once on a particular section the current may rise to a value far beyond that which is safe for the feeder; or if the trolley wire should fall or other fault develop, a section should be immediately cut off without any effect on the dynamos or other parts of the system. A very marked feature to be noted on the switchboard of a railway power station is the rapid fluctuations in the current demand over the various feeders shown by the various ammeters.

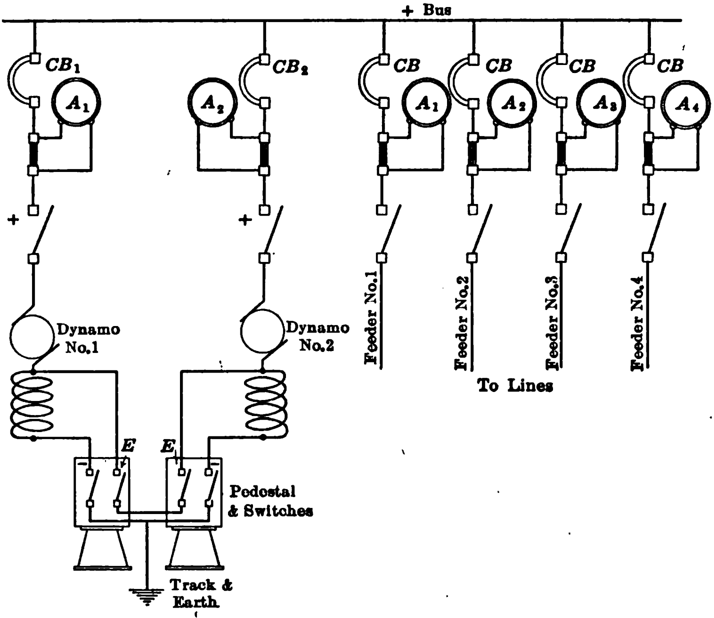

FIG. 99.

81. Finding Circuit Polarity.—In connection with practical work on a constant-potential system it is often important to know which is the + and which the − side of the circuit. The following methods are suggested (which apply to tests on 110-volt circuits). Put a low candle-power incandescent lamp in series with a vessel containing acidulated water, using copper wire electrodes as most convenient. There will be considerable evolution of gas at the negative and the electrode will brighten, while at the positive very little gas forms. If copper wires are thrust into a potato ½ in. apart, a blue ring forms around the positive and white froth around the negative. One may use a polarity indicator, which is likely to be a solution of iodide of potassium with a little starch added. When current passes, the iodide turns the starch blue at the + terminal. Such a solution is often enclosed in a glass tube with platinum electrodes to take current in and out. A piece of blotting paper moistened with such a solution will serve equally well.

82. Insulation and Grounds.—It is most important on a constant-potential system to have all the lines and distributing circuits well insulated so that the current will only flow in the paths desired. Should the insulation become defective between one side of a system and the ground (or any conductor connected with the ground), the system is said to be "grounded" and if the connection is of quite low resistance it would be called a "dead ground." A single fault as at *E* (Fig. 100) cannot cause trouble by permitting a leak of current; and another ground at *b*, for example, would make no difference. But if a ground occurs at *a* there is a leak by way of the two grounds *a* and *E* which may lead to heating effects which cause fire risk or in case both are "dead grounds" to a short-circuit which causes fuses to open and the circuits to be put out of commission. The more complicated the system the more important to keep it clear of grounds.

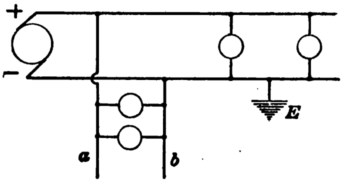

Fig. 100.

In connection with constant-potential systems and the apparatus used on them, many points have not been touched regarding trouble which may arise and how to remedy it. For this the reader is referred to "The American Electrician's Handbook."

QUESTIONS AND PROBLEMS

1. A certain 50-kw. dynamo automatically maintains 125 volts at its terminals. Across the mains (of negligible resistance) I connect

in parallel a lot of lamps (250 ohms each) until the dynamo is loaded to its full capacity. How many have been then connected? Draw a diagram and show some of them connected on four branches.

2. At the busbars of a certain switchboard 115 volts are maintained for a constant-potential distribution. A certain line of No. 4 wire runs 200 ft. (400 ft. of wire) to a branch line *A* on which there are 20 lamps taking 1½ amp. each. It then runs on 100 ft. to another branch *B* on which there are 20 lamps taking 1 amp. each. Make a diagram of the circuit arrangement showing one way of turning off and on lamps on *A*, and a different plan on *B*. Calculate volts at branching point for *A* and at branching point for *B*: (1) with all lamps on (2) with lamps on branch *A* turned off.

3. A shunt dynamo gives 110 volts at its terminals on no load, and if left to itself, 105 volts at full load. A compound dynamo of the same capacity shows 110 volts at no load and the same at full load. Which would be chosen for a constant-potential system and why? Would there be any difference in the choice if lights in one case, or power in another, were supplied? If incandescent lamps or a railway?

4. Why has a shunt dynamo no volts across its terminals and only a small current flowing when short-circuited?

5. A certain shunt dynamo started at 125 volts at "no-load" drops from that to 115 at "full load" of 200 amp. A temporary winding of 50 turns is put on the field winding and 48 amp. are passed through it. With full load the terminal volts are then 125. How many turns of series winding should be provided so that as a compound dynamo, constant potential may be secured?

6. Draw a diagram of a long-shunt compound-wound dynamo. It is a 500-volt, 200-kw. machine using 2 per cent. of its full-load current output for the shunt field. On the diagram mark the amount of current flowing and its direction at full load, in armature, in series field, in shunt field, in external circuit.

7. Make a simple diagram to show two compound dynamos connected for parallel operation, arranged to bring out clearly that the series fields are connected in parallel.

8. At what current would the circuit-breaker be properly set for either one of two 100-kw. 125-volt dynamos operating in parallel? In which one or ones of the three dynamo leads should the breaker be placed? Why is it proper to open the main switch before closing an open circuit-breaker?

9. If upon entering a dynamo room with which one was familiar, two dynamos were found operating in parallel, what means might be taken of telling which had been many hours in service and which one recently connected to the busbars?

10. Referring to Fig. 88 which way must current flow in coil *C* in order to deflect the instrument pointer up the scale? The left-hand magnet pole is *N*.

11. If 5 milamp. pass through an ammeter arranged with a shunt as in Fig. 90, for 50 amp. through the line, what fractional part of the main current will always be found in the ammeter and what in the shunt?

12. A voltmeter having a resistance of 15,000 ohms reads 30 volts when connected between two points of an electric circuit. How much current flows through it? How much will it read and what current flow when connected between points at 150 volts difference of potential? Why does the instrument deflect to read volts correctly?

13. Draw a diagram of a 220-volt three-wire system having five 220-ohm incandescent lamps on the + side and the same number on the − side of the system. Calculate and mark the current flowing along the distributing wires for each point where it is different or changes. (Neglect the resistance of the wires.) Then on a separate diagram turn off two lamps on the + side and mark currents flowing using same plan as before.

14. A certain street car is taking 30 amp. through each of four motors connected, has four heaters of 275 ohms each, an air compressor motor taking 1½ amp. and four strings of five lamps (110 ohms each) all in parallel and all in use. Assuming 550 volts at the car, how much current comes from the station and down the trolley pole to the car?

CHAPTER VIII

DIRECT-CURRENT MOTORS

83. General Facts.—Except for various types of toy motors which depend for their operation on the attractive pull of an electromagnet for an armature and which will not be considered here, electric motors are constructed precisely like dynamos. They may be bipolar or multipolar and have shunt, series, or compound windings on the fields. They may have ring- or drum-wound armatures. The placing of the brushes is the same. Manufacturers use the same frames and the same armature and field windings for both. Catalogues may contain data like this:

Size	Generator rating			Volts	Motor rating, horsepower	Open type, speed
	Volts	Kw.	Speed			
1 F	115	4.5	1175	115	5	1000
2 F	115	6.5	1025	115	7½	875

This data taken from a well-known maker's catalogue describes two frames of his line wound as four-pole shunt machines with wave-wound drum armature winding. For size 1F if run as a dynamo at 1175 r.p.m., 39 amp. at 115 volts is full load; if supplied with current from a 115-volt line as a motor it will be producing 5 hp. at the pulley and be running at 1000 r.p.m. when 39 amp. flow through it. The lower speed as a motor is partly due to the fact that the generator operates with a rheostat in series in the field and so with weaker field, and partly due to causes explained in section 85. One difference between a dynamo and a motor is that whereas the brushes are advanced in the direction of rotation in a dynamo to keep them ahead of the neutral line under load, in a motor they are moved the other way on account of the reversed armature reaction (see section 92).

84. The Rotative Pull.—When a machine is operating as a dynamo, and current is flowing, each wire experiences a pull[1] resisting the rotation. On this account an engine has to pull the armature around and for this cause power is necessary to propel it. In motors when current is allowed to flow, this same pull is experienced but now for rotation; and it is utilized to pull the armature around. It is a general principle that a conductor carrying current when located in a magnetic field experiences a mechanical force. The direction of the force can be determined by a rule as follows:

Put the thumb and first two fingers of the left hand all at right angles to each other. Point the first finger in the direction of the flux and the second finger in the direction of current flow in the conductor. The thumb will then be pointing in the direction the conductor will try to move. (See section 32 for a similar rule.) This rule may be verified by applying it to the armature shown in Fig. 101 remembering that it applies to wires which are in the flux, that is, on the outside cylindrical surface under the pole faces. With the direction of current flow there shown it will be found that any conductor is pulling for rotation in the direction marked.

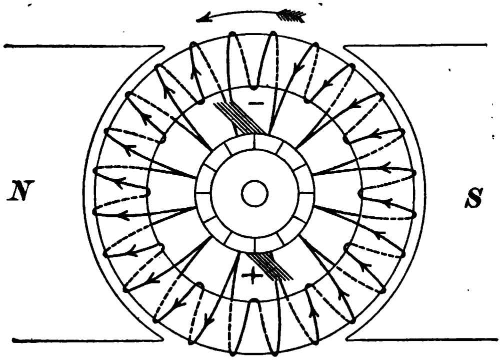

Fig. 101.

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[1] In case of toothed armature cores where the flux passes through the teeth, this pull is almost wholly on the teeth. Refer, however, to section 76 where the principle is stated on which motors are operated.

If reference is made to Fig. 39 it will be found that for the same direction of current flow, when operating as a dynamo, the rotation is the other way. The direction marked in that figure is due to the engine which is overcoming the resisting pull in the conductors of a dynamo as already explained.

The amount of the force exerted by a conductor carrying current in a magnetic field is determined by the amount of current flowing and the strength of the magnetic field. If there are a number of conductors in the same field pulling together, the total pull is that of any one multiplied by the total number, or is proportional to the number pulling. Examination of the flow of current in the armature winding of a motor, as in Fig. 101, will show that in it, if the brushes are in proper position, all the wires pull in the same direction for rotation. Reversing the current in either the armature winding or field winding will reverse the pull and so the rotation of the machine.

85. The Motor E.m.f.—When the armature of a motor is revolving, an e.m.f. is being generated in the armature winding just the same as though it were propelled at the same speed by an engine rather than by current flowing through it. An examination of Fig. 101, using the rules appropriate to determining the presence and direction of e.m.f. generated, will show that the motor e.m.f. is a counter e.m.f., that is, one directed against the flow of current. The magnitude of this e.m.f. is calculated exactly as for the same machine operating as a dynamo. Thus, suppose the machine 1 F referred to in section 83 when running as a dynamo is generating 117 volts when 20 amp. are flowing through the armature and 115 volts are found at the terminals. This will be the case if the armature resistance is $\frac{1}{10}$ ohm. We assume the speed then to be 1175 r.p.m. as given in the table. Now if operating as a motor, from a 115-volt circuit, the field (if rheostat is left in) receives the same current as it did before and the field flux is the same. The motor-generated e.m.f. is then bound to be 113, for of the 115 volts applied two are used up in getting 20 amp. through the armature resistance. The generated e.m.f. and speed change together; and so with 20 amp. flowing in the armature the speed must be 1134.8 r.p.m. This is obtained from

$$117 : 113 = 1175 : x$$

Notice from this result how it is certain that the motor speed at a given terminal voltage will be less than the speed as a dynamo.

86. The Motor Current.—In the case of a motor as already inferred, two e.m.f.s as well as the armature resistance are linked with the current flowing. To determine the amount of current flowing, a calculation may be made by using the following formula:

$$I = \frac{E - e}{R}$$

in which E = e.m.f. applied to armature; e = motor e.m.f.; R = resistance of armature.

For an example, take the motor for which a calculation was made in the last section. Substituting data there given,

$$I = \frac{115 - 113}{1/10} = 20 \text{ amp.}$$

All practical motors of the present day operate on constant-potential circuits. Hence E in the above formula is constant. Since the motor armature resistance is fixed, the current (I) can only change by a change in the motor e.m.f. (e).

The way in which a motor automatically adjusts the current flowing through it to the demands of the load may be illustrated by first considering a simple mechanical example. Suppose a man is turning a grindstone. He must exert a pull for rotation so that in spite of friction of bearings and air resistance the stone keeps revolving. He is supplying it with power to propel the friction load. If now a tool to be ground is set down on the stone the pull he is exerting is not enough to keep the stone moving, and so it slows down. This is the signal to the operator to pull harder in order to supply the power required by the increased load. After he has adjusted the pull he exerts on the crank to this new requirement, suppose the tool is removed from the stone. The pull for rotation is now much above the requirements of the load and the stone speeds up or accelerates. This is the signal to the operator to reduce the pull.

In making an application of this principle it will be best to consider each type of motor separately.

87. Shunt Motor on Constant-potential Circuit.—Suppose we consider a motor having an armature resistance of ½ ohm working with an applied e.m.f. of 100 volts. Start with the motor "running free" on the line. Some current is flowing through the armature to supply the pull necessary to propel it against its bearing friction, etc. Suppose this is 2 amp.

$$I = \frac{E - e}{R} \qquad\qquad 2 = \frac{100 - e}{\frac{1}{2}}$$

from which $e = 99$ volts. Suppose now a belt connected to some machinery is thrown on the motor pulley. The 2 amp. flowing do not exert a pull great enough to keep the motor and machinery going, and they slow down. This is the signal to the motor to pull harder by receiving more current, for since the motor e.m.f. and speed are proportional, a diminution in speed diminishes e. Suppose it drops to 95 volts. The current then flowing will be

$$I = \frac{E - e}{R} = \frac{100 - 95}{\frac{1}{2}} = 10 \text{ amp.}$$

This current gives the armature the means of pulling five times as hard as before, and so (if 10 amp. is right for the load) the motor runs on at the reduced speed. Further, we can tell what the reduced speed is. Suppose the speed when running free was 1000 r.p.m., then this proportion holds:

$$99 : 95 = 1000 : x$$
$$x = 959.6 \text{ r.p.m.}$$

x is the speed when 10 amp. flow in the armature.

Suppose now the belt is thrown off: 10 amp. are flowing through the armature, much more than necessary to furnish the pull for a motor running free. Hence the armature accelerates. And this is the signal to reduce the pull by reducing the current, for as the speed rises the motor e.m.f. rises and causes the current to drop. When 1000 r.p.m. are reached the motor e.m.f. is back to 99 volts and the current has been reduced to 2 amp., which is the amount now required.

From these considerations we see how the current is automatically adjusted to the load and that the motor must slow down as the load increases. This decrease in speed is not great, however, so that shunt motors are in very wide use for all sorts of industrial purposes as "constant-speed motors." In small motors the change in speed from no load to full load will not exceed 6 per cent., while in large ones it is less.

88. Shunt Motors in Special Uses.—A decrease in volts applied to the armature of the motor will decrease the speed in nearly the same proportion, the current in the field coils being assumed constant.

Thus, suppose the motor above working with a load to pull for which 10 amp. are required. As already determined, the speed with 100 volts applied is 959.6 r.p.m. If 50 volts were applied (half as much) the speed may be determined as follows:

$$I = \frac{E - e}{R} \qquad 10 = \frac{50 - e}{\frac{1}{2}}$$

$$e = 45$$

$$99 : 45 = 1000 : x$$

$$x = 454.5$$

which is the speed in r.p.m. with 50 volts applied. The applied volts were halved and the speed is a little less than half as much as before.

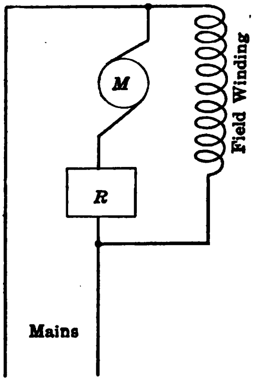

Fig. 102.

A decrease in applied e.m.f. may be made by putting a resistance in series with the armature (Fig. 102). In this particular case 5 ohms in a resistance would use up 50 volts and leave 50 volts to be applied to the armature.

Weakening the field, as by putting resistance in series with the magnet winding and decreasing current through it, will cause a shunt motor to increase its speed. Weakening the field reduces the motor e.m.f. This causes an increase in current through the armature and a pulling effort is produced more than that which is required for the load. The motor accelerates until the counter e.m.f. is increased to cut down the current again to that required to propel the load, when the motor continues to run at the higher speed.

89. Series Motor on Constant-potential Circuit.—It is much more difficult to calculate problems regarding series motors than for shunt motors, because every change of current through the armature is accompanied by a change of field strength. Suppose a motor running free has a load put on it. It slows down due to the fact that it has not enough current flowing through it to furnish the required pull. But as it slows down and current begins to rise the field is getting stronger, which helps out on the pulling effect but acts against the decrease of motor e.m.f. Hence a much greater change in speed occurs for a given change in current than would be found for the same machine wound as a shunt motor.

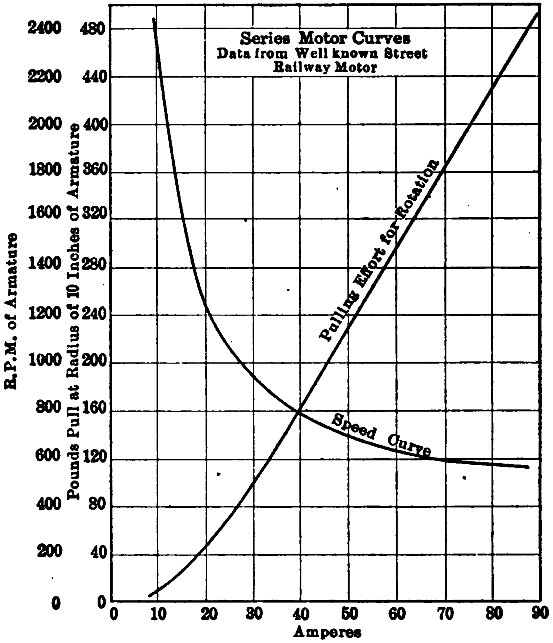

FIG. 103.

Suppose the magnetization of the field is such that an increase in current flowing in the series field winding will increase the field strength proportionately. For doubled current the pull the motor exerts is quadrupled (field strength and armature current both doubled), while the speed must be less than half the former amount, since the motor e.m.f. must decrease in spite of the doubled field strength. The series motor has changes in load accompanied by great speed changes. It can, on the other hand, pull very hard for a given increase in current. On account of these characteristics it has been much used on traction work and for motors on cranes and hoists. Someone is always in charge of such apparatus whose duty is to regulate the speed, especially if it becomes too high. Fig. 103 shows how the speed changes with increasing current, in the case of a well-known series motor used on many street cars. Note the change in speed when the current rises from 50 to 60 amp. (690 to 625 r.p.m.) compared with that when it rises from 10 to 20 amp. (2320 to 1230 r.p.m.). This is because when the larger currents flow the magnetic circuit is nearly saturated; the increase of 10 amp. is therefore accompanied by a very small increase in flux, and so only a small decrease in speed causes the necessary decrease in counter e.m.f.

90. Compound-wound and Interpole Motors.—Motors with compound-wound fields have some practical uses. They are compounded differentially if the series winding magnetizes against the shunt winding, and have a cumulative compound winding if both magnetize in the same direction. Motors with differential compounding have a more constant speed than corresponding shunt motors; they may even increase in speed with increase of load. When load increases the counter e.m.f. must diminish, and if the field is properly weakened as the larger current flows in the armature, this diminution may be accomplished without any diminution in speed. A differential series winding will automatically produce this weakening of the field as the load changes.

A motor with cumulative compounding changes speed with change of load more than would the corresponding shunt motor. Such motors are used for service where a very strong pull is required under certain conditions. In elevator service, for example, a very strong starting pull is secured by this means, and therefore rapid acceleration. At the same time the shunt field maintaining a strong magnetization helps to keep the speed from wide variations after starting and under changes of load; in fact, sometimes current is only allowed to flow in the series field while the motor is starting. A motor driving a set of rolls for bending iron must pull very hard for the very short while the operation is going on and yet must not run at excessive speed when the machine is running "empty." A motor with cumulative compound field winding is best for this, provided with a shunt winding just strong enough to prevent excessive speed being reached on light load.

Many motors which operate with variable field strength are equipped with *interpoles*. Interpoles are auxiliary magnet poles placed between the regular magnet poles of the machine. A four-pole machine, for example, usually has four. They are much more slender than the regular poles and are wound with a series winding. Their purpose is to provide a magnetic flux just right to secure sparkless commutation. In order to have the current in one coil after another reversed as it passes through short-circuit under a brush, it is necessary to have just the right e.m.f. generated in that coil. The resistance of carbon brushes alone will not do it. The amount of this required e.m.f. must be larger as the current to be reversed becomes larger. By using interpoles on which a series winding is placed, just that flux can be provided which will

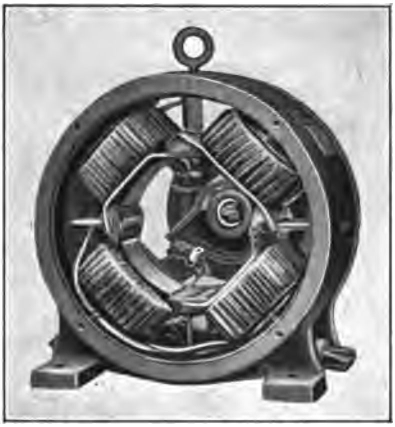

Fig. 104.

generate the proper e.m.f. for any current flowing and for any fluctuations of current without the need of shifting the brushes, so often inconvenient, impossible with rapidly fluctuating loads, and at best a matter of guess work. Fig. 104 shows such a motor. The interpoles are easily identified, between the larger main field poles.

91. Motor Efficiency.—Motors are subject to the same losses as dynamos; hence they have similar efficiencies. There are I^2R losses in field and armature, hysteresis and eddy losses, and friction losses. Motors are always rated on their output. A 10-hp. motor having a full-load efficiency of 85 per cent. would have to receive 10 ÷ 0.85 = 11.76 hp., or 8773 watts. At 220 volts this means 39.9 amp. For motors of ordinary commercial sizes on 220-volt circuits a pretty close estimate of the full-load current they will take is made on the basis of 4 amp. per horsepower.

The efficiency of motors varies with the size of the machine. The following table shows probable values:

⅛ hp., 45–50 per cent.
¼ hp., 60–65 per cent.
1 hp., 70–75 per cent.
5 hp., 82 per cent.
10 hp., 85 per cent.
25 hp., 90 per cent.

92. Armature Reaction and Commutation.—Armature reaction is present in motors as it is in dynamos, but it is of no importance in connection with efficiency. The flux distortion which it produces results in a need to shift the brushes from the no-load neutral line against the direction of rotation to suppress sparking, as may be seen by applying the method of section 37 to Fig. 101. The slight weakening of the field which armature reaction produces will cause a motor to run a little faster than a calculation (which ignores this matter) would indicate. Should the field circuit of a shunt motor develop an open circuit, or that of a series motor become short-circuited, the motor might have enough field due to armature reaction to run without load, but the field would be so weak that the motor would "run away." It would slow down and stop if a load were applied. This effect is more likely to show itself if the brushes have been shifted away from the no-load neutral line.

93. Motor Ratings and Speeds.—Motors are rated at a certain horsepower on the basis of their rise of temperature when operating under full load, never because their limit in power produced has been reached. Most motors can be overloaded several hundred per cent. for a short while without being harmed, provided the sparking at the brushes does not become too serious. Motors for driving machine tools and for continuous service are rated like dynamos (see section 59). Those for traction, crane work, etc., are given special arbitrary ratings which need not be considered here.

The load which any motor can carry continuously is not only determined by the current through it and so the heating effect produced, but by the temperature of the room where it is placed and the way it is enclosed. Some makers supply motors either open, partly enclosed, or completely enclosed. The more a motor is enclosed and the less freedom of radiation of heat and air circulation there is, the smaller the power which can be continuously produced. Here are some figures from a well-known maker's catalogue.

Frame	Speed	Rating in horsepower		
		Open	Partly enclosed	Fully enclosed
AW	650	20	15.5	11.5

Fig. 105 shows the same motor open and also partly enclosed. To be fully enclosed the cover plates must be solid and there must be no opening to the interior around the bearings. It may be noted by referring to Fig. 105 and then to Fig. 104 that the bearings of these motors, as in a majority of modern commercial machines, are simply mounted in end shields; that is, have the bearings mounted in cast-iron end shields which fit against the circular yoke in a machined joint and are held in place by four screw bolts. Hence it is possible to remove the bolts, move the motor around (not the shields), and then replace them so the base of the motor is properly placed for mounting on a side wall or on the ceiling, without interfering with the proper position of the oil reservoir under the bearings.

No estimate of the power of a motor can be made from its size. Suppose a certain motor is a 10-hp. machine making 1000 r.p.m. supplied from a 220-volt circuit. If the armature is removed and another winding put on which has twice as many turns per coil the machine becomes a 5-hp. motor making about 500 r.p.m.

If the original armature winding had a resistance of $\frac{2}{10}$ ohm and 40 amp. is full load, the heat developed there continuously is 320 watts, because $0.2 \times (40)^2 = 320$ watts are spent there. With the new winding and 20 amp. flowing the heat loss is $0.8 \times (20)^2 = 320$ watts. Hence 20 amp. (corresponding to 5 hp.) is all that can be allowed to flow continuously. The speed must drop to about half the former value since twice as many wires are cutting the same flux as before. Hence for the same counter e.m.f. generated the machine makes only half the speed.

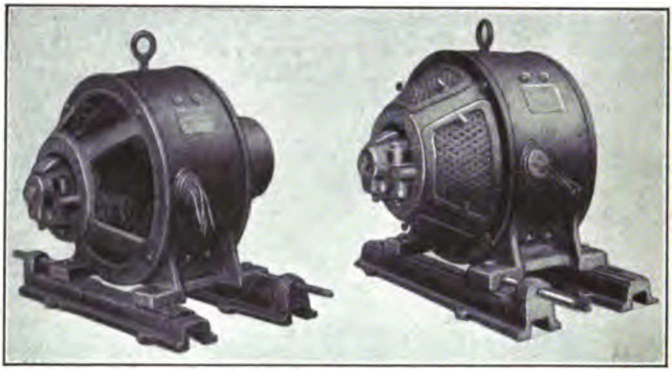

Fig. 105.

It is rather uncommon for the speed of a motor to be the same as that of the machine driven. By considering the data just given it will be seen that a slow-speed motor must always be more expensive than one which runs at high speed. Motors are therefore connected to the apparatus they are to drive by belts over pulleys having suitable diameters, or through gears. Sometimes a countershaft and gear are mounted directly on a motor, the gear meshing with a pinion on the motor shaft. The relation between motor speed and speed of driven apparatus may be determined by the application of one of the following proportions:

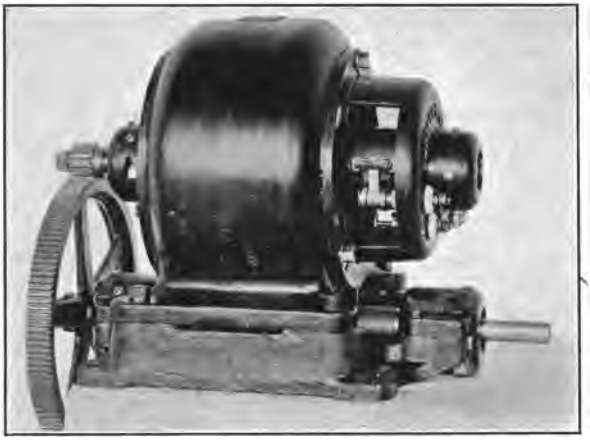

FIG. 106.

$$\frac{\text{r.p.m. of motor}}{\text{r.p.m. of driven shaft}} = \frac{\text{diam. of pulley on shaft}}{\text{diam. of pulley on motor}}.$$

$$\frac{\text{r.p.m. of motor}}{\text{r.p.m. of driven shaft}} = \frac{\text{pitch diam. of gear on shaft}}{\text{pitch diam. of pinion on motor}}.$$

$$\frac{\text{r.p.m. of motor}}{\text{r.p.m. of driven shaft}} = \frac{\text{number of teeth in gear on shaft}}{\text{number of teeth in pinion on motor}}.$$

The pitch diameter of gears is the diameter of the wheels which replacing them and rolling in contact would produce the same speed of the driven shaft as is produced by the gears. It is always wise not to make a very large difference between the diameters of pulleys on motor and shaft because the belt will not drive over the small pulley without slipping. It is never safe to so pick pulleys that a cast-iron rim is to run at more than 3000 ft. per minute.

94. Control of Starting Current.—At the time of starting, a motor cannot be connected directly to the line because an enormous current would flow. A 1-hp., 110-volt motor might have an armature resistance of 1 ohm, and if while at rest and developing no counter e.m.f. it were connected to the circuit, 110 amp. would flow through it, or about 15 times full-load current. This will not do for a number of reasons. A very serious mechanical shock would be given to the motor and all its parts; an abnormal current will blow fuses and make trouble at other parts of the distribution system; the enormous pull would throw off the belt or produce an acceleration of the driven machinery which is utterly impractical for it to sustain. The usual method of controlling the current at start is to put resistance in series with the armature. When motors have shunt fields the fields are connected across the line without series resistance so they may have full strength at starting. Fig. 102 shows the resistance properly placed for starting a shunt motor. Any conductor from a water rheostat to a set of cast-iron grids may be used for this resistance. Its section must be large enough to carry the current which must flow in it without too much heating. Its amount must be great enough to limit the starting current to a reasonable amount. It must be arranged so that as the motor gathers speed the resistance can be cut out one step at a time until the armature is directly across the line. In ordinary practice for motors of moderate size, one and a half times full-load current is allowed to flow through a motor at the instant of starting.

After the motor starts, the current is bound to diminish since the counter e.m.f. rises with increasing speed of the machine. Hence resistance may be cut out step by step, at each one the current rising and then falling again as the motor gains more speed.

If the full-load current of a 2-hp. 110-volt motor is 17 amp., one and a half times full-load current or 25.5 amp. would flow at the instant of starting, if the resistance of the armature circuit were $\frac{110}{25.5} = 4.31$ ohms. If the armature resistance were 0.81 ohm, 3.5 ohms should therefore be put in the starting box.

It is further assumed in good practice that current will not be in the resistance of the starter more than 15 sec. and that it will not have current on except at considerable intervals, and that the rise in temperature under such use will not be more than 300°F. Some machinery such as that having heavy flywheels is very hard to start or must not be started too quickly. A starter specially designed to stand the starting current for a longer time without overheating must then be used.

95. Starter with no Voltage Release.—If an ordinary rheostat is used as a motor starting box there is danger that when the main switch is opened or the power supply is interrupted for any cause the rheostat would be left short-circuited. If then the current were turned on again, fuses will be blown or the motor and connected machinery endangered because the motor is at a standstill and the rheostat short-circuited. Hence common practice makes use of a starter which automatically restores itself to proper starting conditions when the circuit has been interrupted.

Fig. 107 shows such a box and Fig. 108 a diagram of the proper connections. From the diagram it will be clear that after the main switch is closed, the motor circuits are open until the sweep arm *L* is moved toward the right and touches contact *C*. There are then two paths for current, one from *C* through magnet *M* and the shunt-field winding, the other through the resistance of the rheostat and the armature. Since magnet *M* has a resistance whose amount is only 1 or 2 per cent. of that of the field, the motor is started with full-field strength and that amount of current through the armature which the rheostat has been planned to admit. As the arm *L* is moved further, resistance is cut out of the armature circuit and introduced into the field circuit until, when in its extreme "full on" position, the armature on it (*a*) is held against the poles of magnet *M* and this magnetic pull prevents the sweep arm being returned by the operation of the spring wound on its hub which is now in tension. When arm *L* is in this position the motor armature is connected directly across the line and the rheostat resistance is in series with the field. Since this is small compared with the resistance of the field winding it does not produce any material effect on the operation of the motor.

Using such a box the process of starting a motor is to close the main switch and then move the sweep arm slowly over the contacts so that current will not rise too high as step after step is passed, until it is "full on" and the magnet holds it in position. To stop, the main switch is opened. As the motor slows down the spring on the sweep arm *L* presently pulls the arm back to the off position and the motor is ready for starting again. Should voltage fail due to fuses blowing or any other cause the spring will throw the sweep arm back to its proper starting position. It should be noted that when it does so return, because of the way connections are made, the field circuit is not opened; and so there is no flash as the contacts separate, nor is there a high e.m.f. generated in the field winding which might endanger its insulation. It may be further noted that an auxiliary contact button is placed at *C* on which the circuit is finally broken. This is out of line with other contacts so that any burning which occurs there will not spoil the good electrical connection between arm *L* and the regular series of buttons.

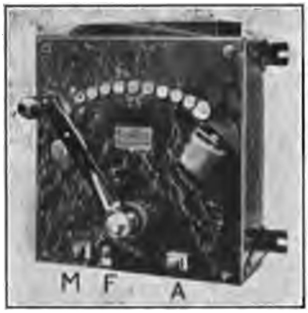

Fig. 107.

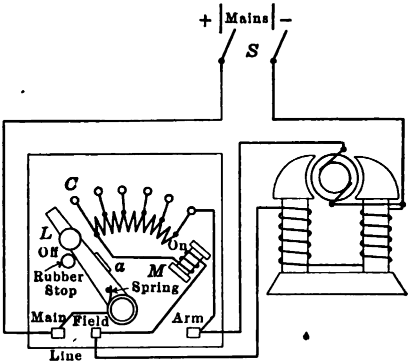

Fig. 108.

There are many ways of designing and building starting boxes. The method used for the particular one just described is shown in

Fig. 109 where the same box is shown but with the front removed. Here are shown a number of asbestos tubes on each of which iron wire is wound in a spiral. All the tubes are alike, but by suitable taps along their length, connecting them in series or parallel, any desired resistance and carrying capacity can be secured. Another construction much more safe against fire risk employs an iron box wholly enclosed, in which wire coils which carry the current are buried in sand. The box now described would only be suitable to manage the starting current for small motors of a few horsepower. It is equally available for compound motors and for series motors if magnet *M*, with resistance in series, is connected directly across the line.

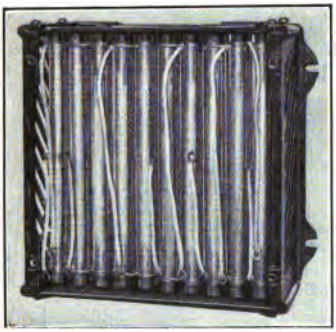

Fig. 109.

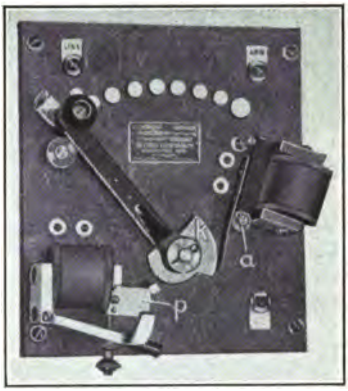

Fig. 110.

96. Automatic Overload Release Starters and Regulators.—A regulator is a rheostat designed to carry current continuously. By using a construction similar to that described in the last section, providing a notched sector or fan tail on the lever (shown at *K* in Fig. 110) and pivoting the magnet armature at *a*, it now being equipped with a spring steel hook, the no-voltage release features are retained while the lever may be placed at any desired position in order to secure speed control. The box in Fig. 110 is also equipped with an automatic overload release magnet and switch which is shown more fully in Fig. 111. Should the main current rise in magnet *N* to a value great enough to raise its armature, the contacts *b* will be bridged and so the magnet *M* short-circuited. This will release its armature and the lever *L* will swing back to the "off" position opening the circuits. The current at which this action occurs is under control by setting the adjusting screw *S* which determines the height the armature must be lifted. The amount of current required to lift it for any setting is given by marked values on a plate *p* (see Fig. 110). This magnet is not only useful as an overload release or circuit-breaker, it also serves a useful purpose as a rough current indicator. On account of corrosion of the contact making parts this device is not very reliable.

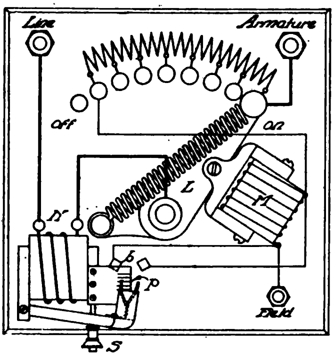

Fig. 111.

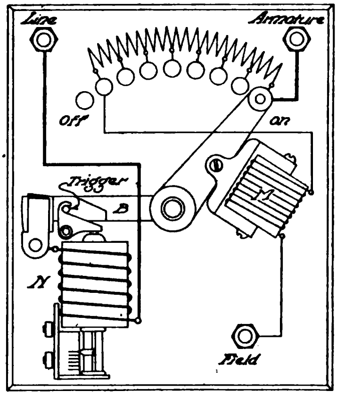

Fig. 112.

A more expensive arrangement of overload release is shown diagrammatically in Fig. 112. The sweep arm is spring connected with an arm *B* which is the blade of a main switch. With the lever in the position shown in the figure the spring is in tension (see Fig. 113). Should current supply fail the armature of *M* is released and the sweep arm returns to its "off" position. Should current become excessive, magnet *N* releases a trigger by the action of an iron rod which is drawn up within it, knife switch *B* opens and the current supply is cut off. (Fig. 114 shows this result.). In this event if the motor is to be restarted switch *B* must first be closed by moving arm *L* to its "off" or correct starting position. For this device to be successful the switch *B* must be very easy to open. It is available only for motors of a few horsepower.

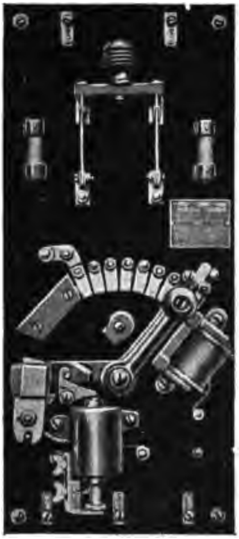

Fig. 113.

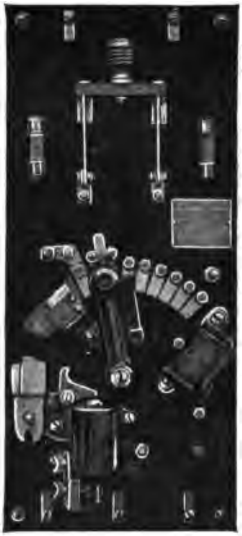

Fig. 114.

97. Automatic Starter with Solenoid.—In many cases motors must be started and stopped from a distant point. Examples may be found in motors driving ventilating fans, elevators, dumb waiters located at some distance from the point where their control is required; or motors on pumps which must be automatically started when a tank empties and stopped when it has been filled. In Fig. 115 is shown such a starter. The main switch shown at the upper left-hand part of the figure is closed within an "arc chute" of non-conducting material by means of a magnet located below it. Current is then admitted to the large solenoid and the motor. The solenoid pulls on its plunger against the restraint of the dash pot,[1] gradually cutting out resistance. Fig. 116 shows the electrical connections. By studying this diagram we may see some important details. After the main switch has been closed current cannot flow until a connection is made between wires *a* and *b*. On making this connection by any sort of switch device current flows from + line through a "blow-out" coil[2] above *d* on through magnet winding *c*, through resistance *n* and out to − line through sweep arm *L*. The magnet operated switch pivoted at *e* and operated by current in *c* immediately closes both at *d* and *f*. In the diagram it is simplified to make the connection clear. Through *d* current passes in three paths; through *e*, *g*, motor armature to *h*, through resistance *j* and out to − line; through shunt field by a path easily traced; through *f*, winding of solenoid *S*, through *r* and so to − line. The motor starts to revolve and solenoid to pull sweep arm *L* over the contact plates at *j*. As soon as *L* begins to move, it parts company with the contact plate shown directly below it and thus a resistance *m* is inserted in series with the magnet *c* of the main switch. As it moves further more and more of the resistance in the starter is short-circuited until as the plunger completes its stroke a flexible copper bridging

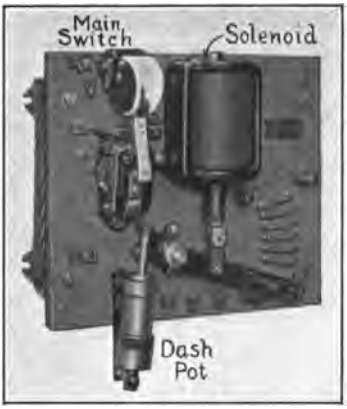

FIG. 115.

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[1] A dash pot is a cylinder within which a piston moves so as to compress air before it. The harder the force applied or more suddenly the piston is moved, the more the air is compressed and the greater the resistance. Only as air leaks out, is the piston able to move on. By means of an adjustable valve in the piston, or in the cylinder or both, the rate at which air escapes and so the amount of resistance the dash pot exerts is controlled. Some dash pots are arranged with valves so that motion in one direction only meets resistance.

[2] A "blow-out coil" is a coil so placed as to produce a magnetic field just where the circuit is broken. The mechanical force acting on a current in a magnetic field is utilized to drive the current in the metallic vapor path or arc in a definite direction and so blow it out or break the arc quickly.

piece spans the space blocks *i* and *q* positively short-circuiting all the resistance in the starter, while a rod on the sweep arm marked *o* striking the piece *r* which is hinged on *q* opens its contact

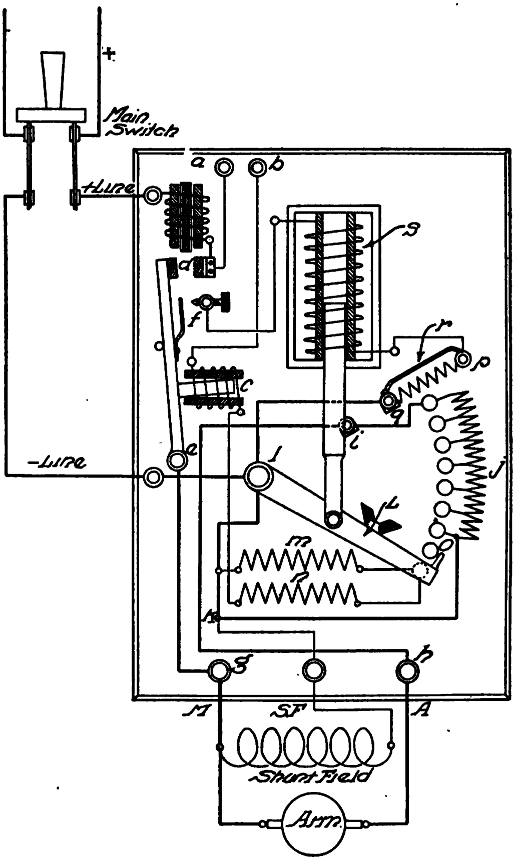


Fig. 116.

at *p* and inserts resistance in series with solenoid *S*. The operation is thus complete. The rate of cutting out resistance is determined by adjustments in the dash pot (see Fig. 115). Hence this sort of starter is often called a time-limit device. The rate of cutting out resistance is independent of the current to the motor. To stop the motor, open the switch connecting *a* and *b*. The main switch then opens, the solenoid lets go and things are at once restored to starting conditions.

98. Reversing Motor Starter.—In many cases when a motor is to be reversed the starter is so arranged that by swinging the sweep arm one way one direction of rotation of the motor is secured, while if swung the other way the motor reverses. Fig. 117 shows how this may be done, the current being reversed through the armature and the same resistance made use of for starting in either direction. If blocks *aa′* on the sweep arm are swinging clockwise, line current comes in through strip *d* to *a*, then to *c*, through the resistance of the whole rheostat to *g*, then through the armature from right to left, to strip *f*, through *a′* to *e* and so on out to the line. Examination of the figure will show, how, as motion is carried further in a clockwise direction, resistance in series with the armature is cut out; or how by a reverse motion of the sweep arm, current flows the other way through the armature and resistance is cut out.

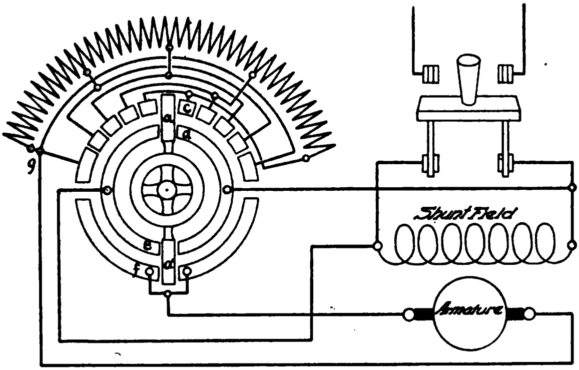


FIG. 117.

99. Motor Starter of Current-limit Type.—In a great many kinds of work a starter is used which operates automatically to cut out resistance, the rapidity with which this is done being under control of the current flowing to the motor and out of control of the operator. Such starters are being used so extensively that one type will be described here. In Fig. 118 the connections for such a starter are shown. The heavy lines show the routes for the main motor current. Each of the switches S_1, S_2, S_3, S_4, is operated by a magnet M_1, M_2, M_3, M_4. Such switches are known as contactors. Fig. 119 shows what one really looks like. T_1, T_2, T_3, are series relays; they are in series with the armature and the main current passes through them. The black rectangle between switch blade and bridging piece at *o*, *p*, and *q* indicates

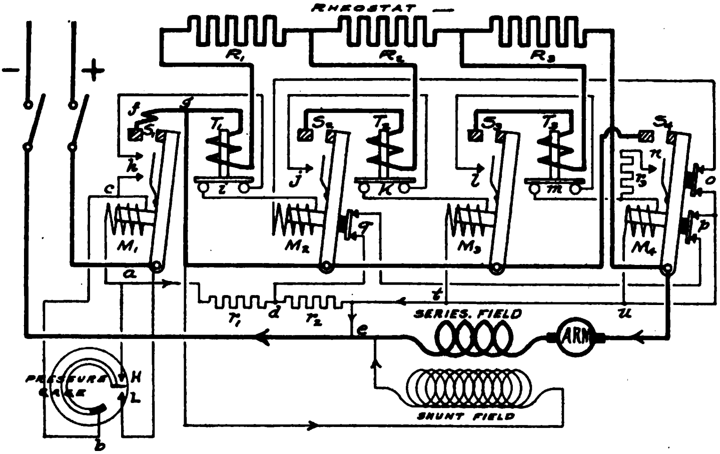


Fig. 118.

insulation. As shown, the starter operates under the control of a pressure gage, the motor being one to drive a pump whose duty is to maintain proper pressure on some apparatus. The method of operation will now be described. The main switch is closed. As pressure falls the curved tube in the gage bends down until a contact closes at *L*. Current then flows from the + main by way of *a*, *L*, *b*, *c*, magnet M_1, resistance r_1, to − line at *e* (note that resistance r_2 is short-circuited by line through *q*, *p*, *u*, *t*). The first contactor now closes and through S_1 current passes through the whole starting rheostat, armature, and series field. The shunt field also is directly across the line. f represents a "blow-out" coil put on this contactor at which the circuit is broken when the motor is stopped. The route of the main current is through S_1, f, g, relay T_1, R_1, R_2, R_3, to armature. When the contactor closed, a circuit through M_2 was closed at h; but the large starting current in T_1 has lifted a plunger and now the circuit through M_2 is open at i. In the meantime, since the motor has started, pressure is rising and the contact at L is opening. Contactor S_1 is kept closed, however, since M_1 receives current by way of the lower contact at h. As the motor speeds up and the current through T_1 diminishes, it lets its plunger drop until i closes. M_2 then receives current and contactor S_2 closes. That section of the rheostat marked R_1 is now short-circuited and the increased current flowing to the motor goes by way of T_2 which lifts its armature from contacts at K thus preventing current flowing through M in spite of the contact at j closing. The opening of contacts at q have put resistance r_2 in series with M_1, but it stays closed with reduced current in it. As the motor further increases in speed and so current drops, the contacts at K close. Current now flows through M_3; another section of the rheostat, R_2, is short-circuited by the closing of contactor S_3; its series relay T_3 rises opening contacts m until current falls again. When these contacts close magnet M_4 receives current, and the closing of S_4 short-circuits the whole rheostat through the heavy connection down from g and them to the right in the diagram. When S_4 closes the contacts at o open. This opens the circuit of M_2. Hence S_2 opens and opening j, M_3 also opens. M_4 does not open since contact n has closed; resistance r_3 has been inserted in series with it, however, so a reduced current flows in it. Contacts at

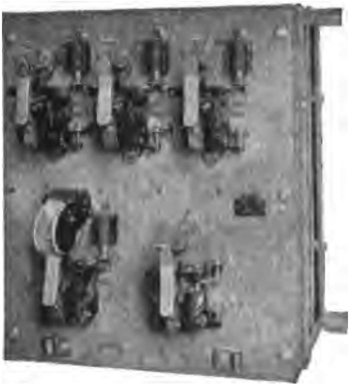


FIG. 119.

p opening prevent a short-circuit on r_2 due to the closing of *q* as S_2 opens. The motor is now operating at full speed; the whole sequence of operations described may not have required more than five seconds, but they have been done in such order and under such control that the current during the starting period has been kept between fixed limits. When pressure has reached the desired maximum contact *H* closes. As a result magnet M_1 is short-circuited, contactors S_1 and S_4 both fall open and the motor stops with the circuits in correct condition for starting.

100. Drum Controllers.—When a motor is not only to be started but in connection with its use various circuit combinations are required, a hand-operated drum controller is commonly used. A drum controller is a sort of cylinder switch by revolving which various connections and combinations are possible. Fig. 120 shows a view of such a controller; at the right stands the cover now removed. In this view the cylinder is shown with a number of copper contact strips mounted on it. At the left side placed in a vertical row are a number of fingers, spring supported (see detail, Fig. 120*a*), which make contact with and bear down firmly on the strips, when by the rotation of the cylinder the strips come under them. Each finger has a circuit connection terminating on it which comes from motor, armature, field, rheostat, or other device. At the top of the cylinder out of sight under the cover (see detail, Fig. 120*a*) there is a star-shaped wheel, in the notches and over the points of which a spring supported roller rides when the cylinder is revolved. When motion is given the cylinder, therefore, a resistance to rotation is felt as this roller mounts one of the points of the star; and as it drops into a notch it defines the point at which the cylinder stops. An operator "feels" these notches and usually speaks of giving the motor 1, 2, 3, 4 notches as the case may be. In Fig. 121 is shown a diagram of a very simple form of drum controller. The fingers are shown as small black circles in a vertical row at the left. The contact strips on the cylinder are spread out at the right, with their interconnections clearly shown. The vertical thin lines marked 1, 2, 3, etc., define the "notches" at which the controller stops, 1 being the first notch as the motor is started. Fig. 122 shows the connections established by setting the controller on the first notch.

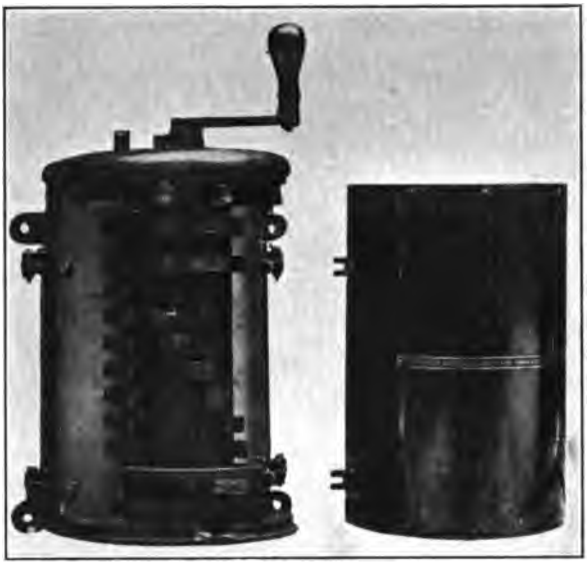


FIG. 120.

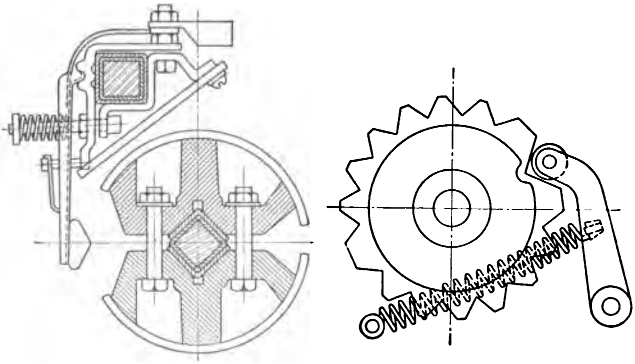


FIG. 120*a*.

Current now flows from + main to finger *a* into strip *m*, to strip *n* through finger *b* to motor armature, back to finger *c* to strip *o*, to strip *p*, into finger *d*, through rheostat and series field to the other side of the circuit. As successive notches are passed more and more resistance is short-circuited until at the fifth notch the whole of it is short-circuited and the motor is connected directly across the line. To make this quite clear suppose the cylinder is revolved to the third notch; then since the strips *m*, *n*, *o*, *p* are all continuous, no change in connection of line to armature or armature to rheostat has occurred. But strips *q* and *r* are both in contact with finger *e* and *f*, hence the real connections are as shown in a simplified diagram in Fig. 123 from which it is clear that all but the last section of the rheostat is short-circuited.

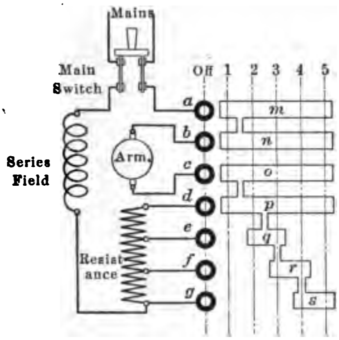


FIG. 121.

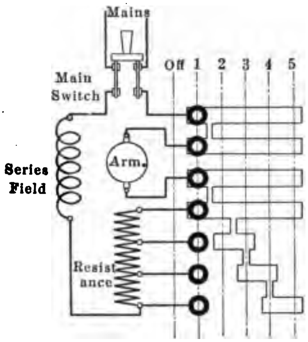


FIG. 122.

If the strips shown had covered only half the cylinder, and on the other half (to the left of the fingers but in reversed arrangement) an exactly similar set of strips had been found, but with the strip *m* connected to *o* and *n* to *p*, revolving the cylinder in the other direction would reverse the direction of rotation of the motor; for current would have flowed through the armature in the reversed direction.

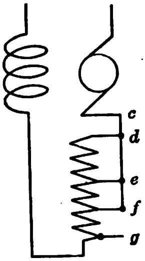


FIG. 123.

Drum controllers are much used with series motors particularly in railway work. Then two or more motors are handled by a controller in order to secure desirable starting conditions and speed changes. In a practical controller the arrangement of contact strips and fingers become quite complicated. A simple diagram therefore, is all that will be given in order to show how a change of connections between two motors from series connection to parallel

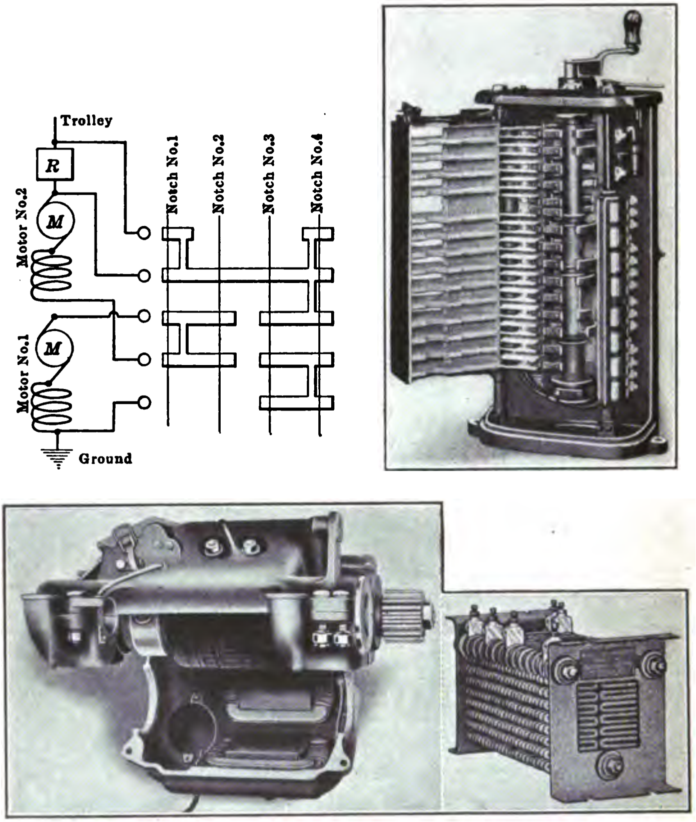


Fig. 124.

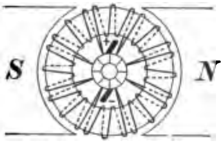
can be made by rotation of the controller cylinder. The circuit connections can easily be traced by examining the diagram of Fig. 124. On notch 1 the two motors are directly in series between trolley and track and divide the line voltage between them. On notch 2 (preparatory to connection in parallel) the resistance *R* is introduced in series with them. On notch 3 the motors are connected in parallel, the resistance being in series with both; on 4 the resistance is cut-out by being short-circuited. A form of street railway motor, of drum controller, and of rheostat, are included in Fig. 124. The rheostat would be used in place of *R* in the diagram. The controller provides for cutting off trolley connection, for varying the amount of the rheostat in use, and for reversing the motors.

The drum-controller principle is also made use of in heavy traction work in such way that the controller does not furnish the means of forming contacts for the motor circuits, but becomes a master controller where small currents in control circuits are manipulated and the main-motor circuits are managed by contactors (similar to those described in section 99). The control circuits determine which contactors shall close or open in order to secure a particular set of connections just then required. The subject is far too large and complicated to consider here.

QUESTIONS AND PROBLEMS

1. (*a*) For the motor armature shown, determine the direction of rotation when current flows as indicated. Mark direction of current flow on the winding when determining this.

(*b*) If the magnetic flux were doubled in amount and armature current kept constant, how much would the pull for rotation be altered? How if the armature winding had twice the number of turns shown and the same armature current flowed?



2. A 2-hp. motor on a 220-volt circuit has 6½ amp. flowing to it from the line. Is it heavily loaded or not? What size (current capacity) fuses would you use for this motor?

3. A certain shunt dynamo is generating 240 volts when running at 1200 r.p.m. When it is used as a motor it is running at 1100 r.p.m. How many volts is it generating? Make a diagram to show the motor connected to a constant-potential circuit, marking the + brush and the direction the current flows in the field winding. Also mark the direction of the e.m.f. in the armature.

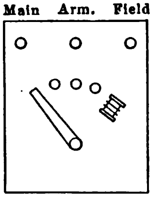
4. A certain shunt motor connected to a 110-volt constant-potential circuit has a field which has 55 ohms resistance and an armature which measures 0.12 ohms. 42 amp. flow to the motor from the line. How much flows through the armature? How many volts back e.m.f. is the motor generating?

5. A shunt motor on constant-potential circuit has a back e.m.f. of 110 volts. The armature resistance is ½ ohm. If the applied e.m.f. is 115 volts, how much current is flowing through the armature? If the field current is 0.8 amp., how much power is being supplied to the motor?

6. A certain 10-hp. shunt motor on 225-volt circuit has 2 amp. flowing through the armature while running "free." It has then a speed of 1120 r.p.m. The armature resistance is ½ ohm. If the load is increased to such an amount that the current flowing is 10 amp., what speed has the motor? What speed when operating under a full-load current of 40 amp.? What is the per cent. decrease in speed from no load to full load?

7. Make a diagram for a shunt motor on constant-potential circuit to show how a simple rheostat could be used for a starting box. How much resistance should it have to hold the current at start to not over 150 per cent. of full load if the motor name plate is marked 5 hp., 220 volts. (Approximate the answer only.)

8. (*a*) Make a diagram of shunt motor connected to line through a starting box of the sort having the external appearance here shown. How much resistance should one have for a 2-hp., 230-volt shunt motor which has an armature resistance of 1 ohm, to keep the current to 10 amp. at starting?



(*b*) Calculate the current flowing (*a*) when the motor e.m.f. has reached 46 volts (*b*) when it has reached 115 volts. The starter is left in circuit without moving the sweep arm.

(*c*) The motor is running with all resistance of the starter cut out. Someone pulls open the main switch. The spring on the sweep arm of the starter does not pull it back to starting position for a full half minute. Explain.

9. A shunt motor on 250-volt circuit is connected to drive a hydraulic plunger pump. The current through the armature is 50 amp. and it is making 1200 r.p.m. A resistance of 2.5 ohms is put in series with the armature in the second case. Calculate counter e.m.f. for both cases. They are in proportion to the respective speeds.

10. A motor like that of the last problem is driving a machine tool and takes 50 amp. through the armature. (*a*) To make it run at 900 r.p.m., how many ohms must be put in series with the armature? (Calculate counter e.m.f. for 1200 r.p.m.; ¾ of this will be the amount for 900 r.p.m. Find the necessary applied e.m.f. and so the number of volts spent in the resistance. The amount of resistance to be used can then be determined.) (*b*) The load now drops so only 10 amp. are required. Calculate the motor speed. (Calculation almost as for No. 9.)

11. How would you manage to reverse the direction of rotation of a shunt motor on a constant-potential circuit? Show diagram with starting box, both before and after the motor is reversed. Make the problem very practical. Think of an actual motor rather than simply of the diagram you have made.

12. An electric motor runs at 1800 r.p.m. and is belted to a countershaft. The pulley on the motor is 6 in. in diameter and the pulley on the countershaft is 24 in. in diameter. What is the speed of the shaft? Recalculate when the motor shaft has a pinion on it with 28 teeth, meshing into a gear on a countershaft which has 168 teeth. The speed of countershaft is wanted.

13. A series motor has a field and armature resistance each of 0.4 ohm. What counter e.m.f. has it on a 125-volt circuit when 10 amp. flow through it? Can you see any reason why it should slow down badly when 20 amp. flow through it? (Consider counter e.m.f. formula.)

14. Two series motors are under a street car. One-fourth ohm is the resistance of each armature and each field. On a certain stretch of track at constant speed and with motors in series the current from the line is 40 amp. How much when the motors are in parallel? (Consider how hard they have to pull in each case to get at the current through each for both cases.) How fast will the car go with motors in parallel if the speed is 8 miles per hour in series? (Calculate counter e.m.f. in both cases and compare them.)

15. Design a drum-controller arrangement for a series motor so that for three positions of the drum the following are secured. Position 1, motor runs in one direction; position 2, motor has current cut off; position 3, motor runs in reverse direction.

CHAPTER IX

MORE PRINCIPLES

101. Calculating Combined Resistance.—By the combined resistance of several conductors is meant that single resistance which might replace them and no alteration in the amount of current flowing in the circuit occur. Certain special and very common cases have been discussed earlier in the book (see Chap. I, section 11). These included the combined resistance of any number of things in series, without regard to the amount of resistance of each one of them, and the combined resistance of any number of things in parallel provided all were of equal resistance. In many cases on constant-potential circuits, no matter how different the resistance of different devices, their combined resistance can be calculated since the current through each can be calculated as well as the total current.

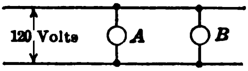


FIG. 125.

Suppose two lamps in parallel on a circuit as shown in Fig. 125. The resistance of A is 120 ohms; that of B is 60 ohms. The combined resistance may be calculated thus. Current through A is 1 amp.; through B, 2 amp.; total current supplied to the two, 3 amp. Resistance equivalent to both together is therefore

$$R = \frac{120}{3} = 40 \text{ ohms.}$$

There are many cases, however, to which no method so far given can be applied. For such cases the following formula may be used:

$$R = \frac{r'r''}{r' + r''}.$$

In this r' and r'' are the separate resistances in parallel and R their combined resistance.

Applying this formula to the case shown in Fig. 125 we write

$$R = \frac{120 \times 60}{120 + 60} = \frac{7200}{180} = 40 \text{ ohms.}$$

The same formula may be employed in calculating the resistance of any number of devices connected in parallel.

In Fig. 126 let the resistances of the various parts be as follows: *A*, 20 ohms; *B*, 5 ohms; *C*, 24 ohms; *D*, 8 ohms; *E*, 5 ohms.

Find the combined resistance from *X* to *Y*.

Take the resistances two at a time.

Combined resistance of *A* and *B*, $R_1 = \frac{20 \times 5}{20 + 5} = \frac{100}{25} = 4$ ohms.

Combined resistance of *C* and *D*, $R_2 = \frac{8 \times 24}{8 + 24} = \frac{192}{32} = 6$ ohms.

Combined resistance of *A* and *B*, *C* and *D*, $R = \frac{4 \times 6}{4 + 6} = \frac{24}{10} = 2.4$ ohms.

Resistance from *X* to *Y*, $5 + 2.4 = 7.4$ ohms.

It may be remarked that the result is independent of the presence of current and without regard to the direction current flows or may flow. The formula holds good for any resistance no matter how high or how low. In applying it in practice with low resistance, the variable and uncertain amount of resistance at contacts and connections must be remembered.

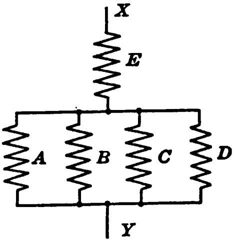


Fig. 126.

102. Change of Resistance with Change of Temperature.—The resistance of all electrical conductors changes with temperature. The change of resistance is due simply to change of temperature without regard to whether this is caused by flow of current or not. Sometimes the change in resistance is enough to require that a definite allowance be made for it. Sometimes it is important to know that the change is too small to count even when the temperature rise is large. Ordinary simple metal conductors such as copper, tin, aluminum, zinc, etc., change resistance about 4/10 per cent. per degree C. change in temperature. All metallic conductors increase in resistance with rise in temperature; carbon, liquids and non-metallic conductors decrease in resistance as their temperature rises. Alloys change in resistance far less than this. German silver changes only about $\frac{3}{100}$ per cent. per degree, while certain alloys used in commercial electric furnaces, etc., may change no more than half as much. Iron changes resistance most of all, altering $\frac{6}{10}$ per cent. per degree.

A motor starting and regulating box is made of iron wire. It has a resistance of 10 ohms. The motor being under full load the temperature of the wire in the starter rises 200°C. The increase in resistance will then be $200 \times 0.6 = 120$ per cent. for the total rise of temperature. Hence the increase in ohms will be 10×120 per cent. or $10 \times 1.2 = 12$ ohms. The resistance when hot will therefore be $10 + 12 = 22$ ohms and this will not only have a serious effect on the operation of the motor but will cause the heating effect (I^2R) in the starting box to be more than doubled.

In rheostats, electric heating apparatus and even more in resistance standards it is very desirable to have material which will change very little with change of temperature.

It must be understood that the statements above are only sufficiently exact for approximate calculations. For exact calculations much more refinement is necessary and for this appropriate treatises should be consulted.

103. Insulation Resistance.—There is no perfect insulator. Air is the best insulator we have; its resistance is beyond measurement. Current flows through insulators according to Ohm's law. Insulation resistance is like conductor resistance in that as the length of path for current increases the resistance increases proportionately, while as the cross-section of the path increases the resistance decreases according to an inverse proportion. Compared with the resistance of conductors that of insulators is enormous. It is measured in megohms (millions of ohms). As an example of insulation resistance, it may be stated that the resistance of a piece of rubber insulation 1 in. long and 1 sq. in. cross-section may be 150,000,000 megohms. To get high insulation resistance, the path through which current passes must be made long and of high resistance material.

The insulation resistance of insulated wire is generally stated in megohms per mile. In Fig. 127 is shown one end of a wire covered with insulation and then with a lead sheath. The insulation resistance would be counted from the wire through the insulation to the lead. The length of the path for current flow is therefore the thickness of the insulation marked l in the view in which the insulation and sheath are peeled off the wire, while the cross-section of the path is the distance around the wire multiplied by its length—$X \times Y$ on the right-hand view. On this basis the following problem may be solved:

A lead-covered cable has an insulation resistance of 50 megohms per mile. (*a*) How much current at 500 volts between conductor and sheath will pass through the insulation of a 20-mile cable? (*b*) Another cable is like the first except that the insulation is twice as thick. Under same conditions how much current will pass through the insulation of a 10-mile cable?

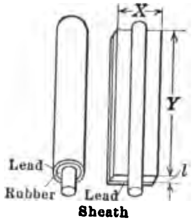


FIG. 127.

(*a*) A 20-mile cable will have a cross-section through which current will pass 20 times as large as a 1-mile cable; hence the insulation resistance will be $\frac{1}{20}$ as much or 2.5 megohms. Through this 500 volts will send

$$\frac{500 \text{ volts}}{2.5 \times 1{,}000{,}000 \text{ ohms}} = 0.0002 \text{ amp.}$$

(*b*) Doubling the thickness of the insulation doubles the insulation resistance per mile. This would make the second cable 100 megohms per mile and 10 megohms for the 10-mile cable. Hence for this case the current through the insulation will be

$$\frac{500 \text{ volts}}{10 \times 1{,}000{,}000 \text{ ohms}} = 0.00005 \text{ amp.}$$

The currents calculated in these examples are very small. Should, however, the insulation resistance of a 20-mile cable prove on measurement to be 2.5 megohms, that is 50 megohms per mile, it would be considered very low, for it may be that the low resistance is nearly all at one spot through which therefore nearly all the current flows. If so, since the insulator is a bad heat conductor, enough local heating may occur to gradually depreciate the insulation, further diminish its resistance and presently a bad ground or burn-out occurs. A low resistance in insulation is called a *fault* or *ground*. It may be so low that instead of millions of ohms it is only a few ohms or nothing.

Insulation resistance of ordinary rubber-covered wires, supposed to be used for circuits at less than 600 volts, will be from 100 to 200 megohms per mile. Extra quality insulated wire and wire for high voltage will run to 1000 or 2000 megohms per mile.

Further consideration of Fig. 127 will show that there is a chance for current not only to pass from conductor to lead through the insulation, but also over its surface at the end. Surface leakage is a very important factor in many kinds of insulation resistance. Fig. 128 shows a cross-section of a common double-petticoat glass insulator. A line of bare wire tied in the groove at *A* has its insulation resistance determined partly by the resistance through the glass to the pin and so to crossarm and to the other side of the circuit or the ground, but much more by leakage over the surface which is made long on purpose to avoid this very thing. A dirty surface slightly moist will make the insulation resistance very low.

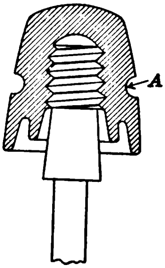


Fig. 128.

There is another property of insulators which is of great importance when high voltage (500 or more) is in use. This is what is known as the breakdown strength. In Fig. 129 let *m* and *n* be conductors laid on opposite sides of a piece of insulation. If one of them is connected to one side of the circuit and the other to the other side the difference of potential acts through the insulation, not only to send a current but to set up a mechanical strain. This strain may become so great as to cause a direct breakdown of insulation. The higher the voltage the greater this strain. It by no means follows that whenever insulation fails it breaks down. Probably in a majority of cases the insulation resistance gradually deteriorates as stated earlier in this section, and a diminishing insulation resistance indicates an approaching failure due to the heating and charring of conduction current. A possibility of direct breakdown may be found between wire and the

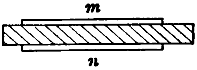


Fig. 129.

lead sheath through the insulation of a cable, between wire and wire of insulated circuits, between bare wires through air space or the insulators on which they are supported. It may be found in any case where conductors are at a difference of potential and are supported on insulating materials.

104. Division of Current in Branched Circuits.—The division of current in parallel or branched circuits is sometimes impossible to determine without the aid of a formula. Fig. 130 shows a rheostat *R* in series with a branched circuit of two resistances r' and r''. No matter what the real value of *R* or r' or r'' may be or at what value *R* is set, the fall of potential from *a* to *b* through either path must be the same. Call this fall of potential for conditions shown *e*, the current in r', i' and that in r'', i''. Then

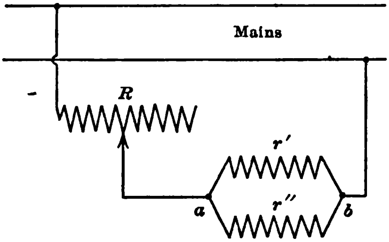


Fig. 130.

$$e = i'r' \qquad e = i''r''$$

Things that are equal to the same thing are equal to each other. Hence

$$i'r' = i''r''$$

from which it follows that

$$\frac{i'}{i''} = \frac{r''}{r'} \text{ or } i':i'' = r'':r'$$

If r' is 1 ohm and r'' is 3 ohms, how much of the current which passes through *R* flows in r' and how much in r''?

$$i' : i'' = 3 : 1$$

that is, ¾ of the current is in i' and ¼ in i''.

The current in each branch may be worked out by the aid of a formula below which can be derived by algebraic methods from those just put down. (I is the current in the line, or the sum of the currents in the branches.)

$$i'' = \frac{r'}{r' + r''}I \qquad i' = \frac{r''}{r' + r''}I$$

Referring to Fig. 130, if the current through R is 10 amp., r' is 2 ohms and r'' is 6 ohms, what current flows through each?

$$i'' = \frac{2}{2+6} \times 10 \qquad i' = \frac{2}{2+6} \times 10$$

$$= \frac{20}{8} = 2.5 \text{ amp.} \qquad = \frac{60}{8} = 7.5 \text{ amp.}$$

For a check $I = i' + i'' = 7.5 + 2.5 = 10$ amp.

When a second path is provided for current in parallel with one which is perhaps the natural or important one, that path is called a shunt upon the other. A shunt field of a dynamo has been repeatedly referred to; it is a path for current in parallel with the main circuit which diverts or shunts some of the armature current away in order to magnetize the field. In many cases the shunt has lower resistance than the thing shunted. A particular case is that of an ammeter and its shunt. Fig. 131 shows the arrangement. The current divides between shunt and ammeter so that very little passes through the instrument. The shunt is made separate so that an instrument can be disconnected without disturbing the circuit.

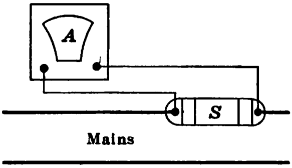


Fig. 131.

Suppose the shunt shown in Fig. 131 has a resistance of 0.00012 ohm and the ammeter 20 ohms. When 500 amp. flows down the mains 0.03 amp. flows through the ammeter. Suppose then the pointer stands at the end of the scale where 500 is marked. If now the current drops to 250 amp. in the mains, that in the ammeter will drop to 0.015 amp. and so the pointer will be halfway along the scale where the mark 250 appears.

105. Electromotive Forces in Parallel.—When two sources of e.m.f. are connected in parallel as shown in Fig. 132, the division of current between them, and even the direction of current, is determined by the resistances in each source and the amount of each of the e.m.fs.; but however this may be, the difference of potential between *a* and *b* must be the same no matter through which source we go. This may be illustrated by numerical examples to further explain the facts regarding the operation of dynamos in parallel as stated in section 72.

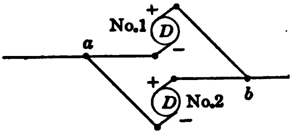


Fig. 132.

1. Let each dynamo, No. 1 and No. 2, be generating 120 volts and each have a resistance of 0.02 ohm. If no load is connected no current will flow, for around the only path there is 120 volts opposing 120, and 120 volts is the difference of potential between *a* and *b*.
2. Suppose now such a load is connected that 400 amp. flows to it. If 200 amp. flows through each machine 200 × 0.02 = 4 volts must be spent in each and so each one is generating 124 volts if 120 volts is still found between *a* and *b*.
3. The same current still flows to the load and 120 volts is found between *a* and *b*. If No. 1 generates 122 volts, 2 volts are used in getting current through its 0.02 ohm or 2/0.02 = 100 amp. flows through it. If No. 2 generates 126 volts, 6 volts are used in getting current through its 0.02 ohm or 6/0.02 = 300 amp. flows through it. The conditions as regards load and terminal voltage are thus satisfied.
4. Same current to load, and volts from *a* to *b* the same. If No. 1 generates 120 volts no current can flow through it for there are also 120 volts at its terminals. If No. 2 generates 128 volts, 8 volts are gone in it and so the current flowing through it must be 8/0.02 = 400 amp.

From this set of examples it is easily seen that by lowering the volts generated by No. 1 and raising the volts generated by No. 2, the load (the current) is shifted from No. 1 to No. 2 until it may all be carried by No. 2 and none by No. 1. Should the e.m.f. of No. 1 be further lowered and of No. 2 raised, terminal volts still remaining at 120, the current from No. 2 would become larger, all above 400 flowing back through No. 1 and driving it as a motor.

106. E.m.f. Generated by Change of Flux.—In an earlier section (section 31) the generation of e.m.f. by cutting flux was explained. E.m.f. may also be generated by changing flux through turns of conductor; in fact, in a majority of cases a clearer perception of the facts is obtained by thinking of the e.m.f. being generated by this cause.

In Fig. 133 an iron ring is shown with two coils wound on it. Suppose the switch *S* to be closed. Current begins to flow in the coil *A* in the direction marked, and this sets up flux around the ring, clockwise as marked. The flux grows as the current in *A* grows. At the same time this same flux is increasing through coil *B*, and this will cause an e.m.f. in *B* in such a direction that if it makes current flow this would oppose the growth of flux. To oppose the growth it would have to flow so that the flux it would send would be against that set up by coil *A*. Hence the direction marked for e.m.f. in *B* is as marked in the figure. As soon as the current in *A* is established and has a fixed value, the flux it sends around the ring is fixed in amount also; and so since the flux through *B* is no longer rising, the e.m.f. which was there while conditions were changing in *A* is gone.

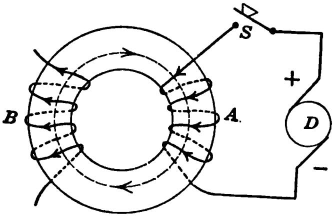


FIG. 133.

In a similar way if the switch is now opened the current in *A* will cease and the flux through the ring drop to nothing (except for residual magnetism). Flux then drops to nothing through *B* also, and while flux is changing in it an e.m.f. will again exist there. If it sends a current it will be in such a direction as to oppose the diminution in flux; hence the current would be directed so as to send flux the same way as marked or with the dying flux. The e.m.f. in *B* is therefore directed the opposite way to that marked when the circuit of *A* is broken. We see from this analysis, then, that a varying current in one coil will set up e.m.f. in another coil placed so flux from the one can pass through it, and that this e.m.f. will only exist while current is varying. Furthermore, the direction of this generated e.m.f. is one way at make of circuit in *A* (growth of current there) and the other way at break (dying out of current there).

The magnitude of the generated e.m.f. in *B* will depend on the number of turns in it: the more turns the more e.m.f. It also depends on the amount of flux through the ring due to *A*: hence the more ampere-turns in *A* under steady conditions of current flow the more e.m.f. in *B* at make or break of circuit. It is also dependent on how quickly the flux changes: the quicker the change the larger the generated e.m.f.

We may further note that when flux is changing through *B*, due to the increasing or diminishing current in *A*, it is also changing through the turns of *A*. Hence e.m.f. is set up in coil *A* at the same time as in *B*. Making an analysis of its direction by the plan already stated, we will find that it will be directed against the dynamo e.m.f. at make of circuit and with the e.m.f. at break. The amount of e.m.f. *per turn of coil* must be the same in *A* and *B* for it is due to the same flux changing at the same rate in both. The e.m.f. which a varying current in a coil induces in the coil itself is called its e.m.f. of self-induction. At make of circuit it can never be as large as the e.m.f. due to which the current flows, for it is due to a growing current. At break it may be of any amount depending on the rapidity with which the circuit is broken. A spark prolongs the break; a sudden opening of circuit or a means of suppressing the spark will greatly magnify the e.m.f. induced.

The shunt field coils of dynamos which have in them a large number of turns on magnetic circuits through which large amounts of flux go may generate enormous e.m.fs. at break of circuit, enough to break through their insulation and ruin the coils. To generate a volt, flux must change at the rate of 100,000,000 lines per second.

A certain dynamo has a field winding containing 4500 turns of wire; 1.5 amp. flows through the winding sent by 125 volts; the flux through the magnetic circuit is 1,500,000. If the circuit is opened in ⅕ sec., what e.m.f. is just then found between the terminals?

To lose a flux of 1,500,000 in ⅕ sec. is at the rate of 7,500,000 per second, which would mean 0.075 volt per turn of coil e.m.f. of self-induction generated. The total e.m.f. between terminals must then be

$$0.075 \times 4500 + 125 = 462.5 \text{ volts.}$$

This is the average value through the fifth of a second. It is likely to be very much higher at the very instant the switch contacts part.

QUESTIONS AND PROBLEMS

1. A 60-watt incandescent lamp and a 40-watt lamp are in parallel on a 120-volt circuit. Calculate their combined resistance, using two methods of section 101.

2. On one branch of a certain circuit there are connected in parallel from + to − lines five heating units having 150 ohms each. On another branch connected from + to − lines are four lamps having 240 ohms each. Calculate the combined resistance of all.

3. Calculate the combined resistance of a circuit like that in Fig. 126 except that *A* is 4 ohms, *B* is 12 ohms, *C* is 9 ohms, *E* is 7¾ ohms, while in *D* there is an open circuit.

4. A copper line wire of No. 1 wire is exposed to outdoor temperatures. At −20°C. it measures ¼ ohm. What will its resistance be when the summer temperature of 40° is reached?

5. The insulation resistance of a piece of rubber-covered wire, measured by immersing it all except the ends in a bucket of water and measuring the current a battery sends from the wire to the water through the insulation, is 6000 megohms. The length of immersed wire is 176 ft. Calculate the insulation resistance per mile.

6. On a certain 115-volt insulated lighting circuit a dead ground develops on the positive side. Can you think of any reason why this is undesirable?

7. Twenty amperes are flowing through a certain circuit. At a certain point it divides through two branches. One branch (*A*) has 4.5 ohms resistance; the other (*B*) has 0.5 ohm resistance. How much current flows in each branch? Recalculate if the current stays the same but the resistance in branch *A* is changed to 2 ohms.

8. Two dynamos are connected in parallel as shown in Fig. 132. We happen to know that the resistance of No. 1 is .25 ohms; and 20 amp. flow through it from *a* to *b*. Also we know that the resistance of No. 2 is 0.3 ohm and 25 amp. flow through it from *a* to *b*. No. 1 is generating 225 volts; No. 2, 227.5 volts. Calculate the current to the load and the volts a voltmeter would read if connected from *a* to *b*.

9. A coil arranged on an iron core as shown in Fig. 133 has in it 1500 turns and 2 amp. are flowing through them. A flux of 500,000 lines is in the iron core. When a switch in the circuit is opened the current drops to nothing through the arc which forms, in $\frac{1}{10}$ sec. Counting that all the flux goes in this time, what average e.m.f. in volts was generated? If in the first $\frac{1}{100}$ sec. as the switch blades parted the flux dropped to 100,000 lines, what was the average e.m.f. in *this* period?

CHAPTER X

ALTERNATING-CURRENT PRINCIPLES

107. Alternating and Direct Current.[1]—A direct current is one which flows steadily through a conductor in one direction having some particular constant amount. If it is 3 amp. it is that at every instant no matter how exactly or carefully it is examined. An alternating current varies in value while flowing one way, increasing in amount to a maximum then decreasing to nothing; it then reverses and flows the other way increasing again to a maximum and decreasing to nothing. These reversals and variations repeat themselves at regular intervals as long as the source is connected to the circuit. The maximum value reached by the current when flowing one way is the same as that which is reached when it is flowing the other way.

The best illustration which can be given of the way such a current flows is probably by using as an example the flow of a water stream. Direct current is like the water current of a river, constant in amount and always flowing the same way. The current (amount of water flowing past a point per second) is the same at any instant. Alternating current is like the water current in a stream connecting the sea with an inland bay. At ebb tide there is no current. As the tide turns the current starts to flow from the sea toward the bay and gets larger and larger until at half tide it reaches a maximum value. After this and up to flood tide the current still flows from the sea to the bay but in decreasing amount until when flood tide is reached the current ceases. When the tide begins to ebb, the current starts to flow from bay to sea increasing in amount until at half tide it is a maximum, decreasing after that until it ceases as ebb tide is reached again. This water current has fixed time intervals between maximum values or between zero values, and reaches the same maximum when flowing one way as it does when flowing the other.

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[1] In making a comparison no account is taken of conditions at the time of make or break of a circuit or of those which exist just as the resistance of a circuit is altered.

An alternating current must have a circuit to flow in as does a direct current. At any instant of time an alternating current has the same value all through the circuit. If it is 2 amp. just now at one point, flowing a certain way around the circuit, it is 2 amp. also at every other point. It is very important to gain a correct idea of the above facts about alternating current before learning about any methods of representing it.

An alternating current flows only because an e.m.f. sends it. Any alternator, or alternating-current dynamo is used for the purpose of generating an alternating e.m.f.[1] The current flows in the direction the e.m.f. acts and has its amount determined by the e.m.f. from instant to instant. Hence to have an alternating current in a circuit there must be an alternating e.m.f. there.

A.C. is a common abbreviation for alternating current, as D.C. is for direct current. These abbreviations will be freely used in subsequent sections.

108. Representing Alternating Current.—Because alternating current varies as it does, it is necessary to have some way of representing it in order to understand many important things regarding it. The simplest way is to picture it by plotting time on a base line and amount of current vertically. This is done in Fig. 134. Starting from the left, time starts when no current flows. After $\frac{1}{480}$ sec. has passed the current has increased, flowing a certain way, so that it is now between $2\frac{1}{2}$ and 3 amp. As time goes on the current keeps increasing, still flowing the same way, until when $\frac{2}{480}$ sec. has passed the current has risen to 4 amp. which is its maximum value. Time goes on and when $\frac{3}{480}$ sec. has passed the current has diminished to less than 3 amp., while after $\frac{4}{480}$ sec. the current has ceased to flow. The curved line indicates the current flowing at *any* instant of time; heights to it from the base line show the amount of current flowing. At the time when the curve intersects the base line, no current is flowing. After this the current reverses and after $\frac{2}{480}$ sec. more ($\frac{6}{480}$ from the start) it is 4 amp. again (its maximum value) but flowing the opposite way through the circuit, and therefore shown *below* the base line. Another $^2/_{480}$ sec. and it has dropped to nothing and starts flowing again as at first. The intervals between maximum values of current or of zero values are the same. Because the picture suggests it a wave of A.C. is sometimes spoken of. This does not mean that current flows in waves through a circuit, however. At the end of $^2/_{480}$ sec. for example, 4 amp. is flowing at every point around the circuit.

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[1] For a general idea of the appearance of an alternator refer ahead to Figs. 214, 217, 218.

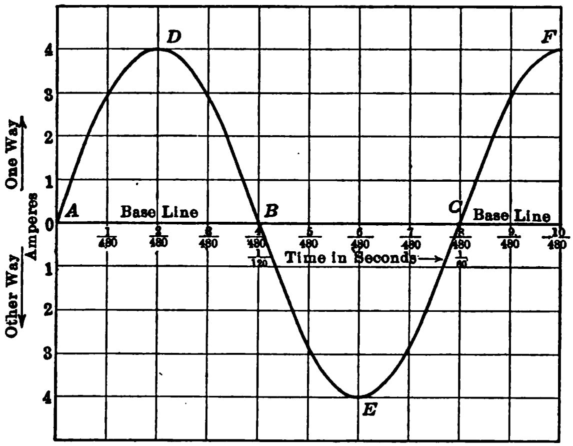


Fig. 134.

An alternating current is such no matter what the form of the current curve, provided it repeats itself at fixed intervals according to the same methods of growth. Thus in Fig. 135 an alternating current is shown which reaches its maximum quickly and dies out gradually. Yet it fulfils all the conditions which have been stated regarding equal maximum values in each direction and equal length of time from maximum to the next one, etc. An alternating current is such no matter whether the reversals of current are at long intervals or occur thousands of times per second. The one represented in Fig. 134 is a very common sort, the current rising to maximum and dropping again to nothing in

$1/120$ sec. Considerable pains is taken to have current in practical circuits the sort which is represented by Fig. 134. Problems always assume it. The way in which current flows in this ideal

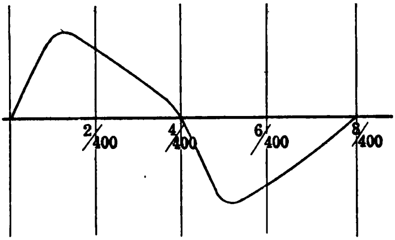


FIG. 135.

case may be shown by a plot in Fig. 136. At equal time intervals six values of current in per cent. are put down. Knowing the maximum value of any alternating current which has the ideal form all its other values can readily be found from this.

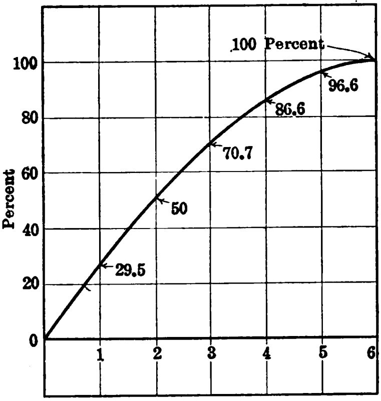


FIG. 136.

The same method of representation which has been described for alternating current is also used for alternating e.m.f. Both current and e.m.f. may be shown in the same diagram. Since an alternating e.m.f. sends an alternating current, they would reach maximum values together and cross the base line at the same point.

109. Important Definitions.—The following definitions apply equally to alternating current and e.m.f.

Alternation.—An alternation of A.C. is completed when a set of variations from one value to a corresponding one has been completed. An alternation is comprised between one maximum value and the next (*D* to *E* or *E* to *F* in Fig. 134) between one zero value and the next (*A* to *B* or *B* to *C* in Fig. 134. No time consideration belongs to an alternation.

Cycle.—Two successive alternations. A cycle has been completed when an alternating current has progressed from one maximum value to the next one at which the current is directed the same way through the circuit (*D* to *F* in Fig. 134) or from any value to the next one like it in every particular.

Period.—Time of a cycle in seconds. The period of the alternating current represented in Fig. 134 is 1/60 sec.

Frequency.—Rapidity of alternations. The number of cycles per second; or much less often, the number of alternations per minute. The symbol for frequency when cycles per second are meant is ~. Commercial frequencies are 25, 30, 40, 60, 120, 133, 140 cycles per second. Twenty-five cycle current is said to have low frequency; 60-cycle current moderate frequency; and 120-cycle current high frequency for lighting. Frequencies of 25 and 60 are in common use at the present time; others are little used and some are nearly obsolete. The frequency of the current shown in Fig. 134 is 60 cycles per second.

Since e.m.f. sends current both must have the same frequency.

Phase.—That value which an alternating current has at any particular instant of time, used to distinguish it without saying how much it is. Thus in answer to the question, "In what phase is the current at the instant considered?" we might reply "At maximum." A common expression is *difference in phase.* If two alternating currents are under consideration and one reaches maximum before the other, we say there is a difference in phase between them. If the difference is quarter period, one reaches maximum as the other passes through zero value. The expressions lag and lead refer to phase differences. If a current lags behind another, it reaches maximum value later; if a current leads another it reaches maximum value earlier.

110. Naming Amount of Current and E.m.f.—In view of the fact that alternating current constantly varies both in amount and direction, to speak of some certain number of amperes of A.C. flowing in a circuit would be meaningless unless some plan is made use of which has been adopted by general agreement. It is agreed that an alternating current shall be called that number of amperes of direct current which, replacing it, would have the same heating effect. Thus an ampere of alternating current is that amount which will cause an incandescent lamp to burn just as brightly as 1 amp. of direct current. If 20 amp. of direct current melt a fuse, 20 amp. of alternating current will do the same.

If desired, the relation which exists between the maximum value of a current and this value by which it is called may be found. As already explained, it is the heating effect of current by means of which it is designated. The heating effect varies with the square of the current flowing. In Fig. 137 the curve *abc* shows an alternating current whose maximum value is 5 amp. and which rises and falls in the customary way as noted in section 108. The curve *apc* is one of squared current values; made from the other by squaring a number of values and plotting them to get the curve. Thus at maximum $5^2 = 25$ which is the height *dp*; *mo* is $4.62^2 = 21.34$; *jl* is $3.54^2 = 12.53$; *gi* is $1.91^2 = 3.65$; *ef* is $1^2 = 1$. Through these points and others like them on through to *c* the curve is drawn. Now at any instant the height of this curve represents the heating effect of the current just then. We are seeking a value to represent the average heating effects. This may be obtained by calculating the area of the curve *apc* above the base line and then dividing this by the length of the base line *adc*; for

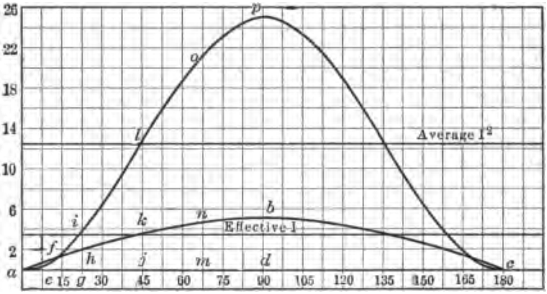


Fig. 137.

the result is the average height and so represents the average heating effect. Such an area can be measured by certain instruments or calculated by the aid of higher mathematics. Should a calculation be made the average height would turn out to be 12.50. The steady current which would produce a heating effect the same as this represents is $\sqrt{12.50} = 3.535$ amp. This is the direct current which could replace the alternating-current flowing, whose steady heating effect would be the same as the variable heating effect of the alternating current. It is called the effective current, since it is as effective (produces the same effect) as the real alternating current. The ratio between the maximum and the effective value is now obtainable. For this case $\frac{3.535}{5} = 0.707$, and the same ratio holds good for all amounts of alternating current. An alternating current whose maximum value is 10 has an effective value of 7.07 amp. One whose effective value is 10 amp. has a maximum value of $\frac{10}{0.707} = 14.14$ amp. The maximum value can always be reached from the effective by multiplying by 1.41 and the effective value can be reached from the maximum by multiplying by 0.707.

There must be also a numerical method of designating alternating e.m.f. It will be clear without detailed explanation that the same method of designating e.m.f. as that explained for current should be made use of. In common usage then, alternating e.m.fs. are always called by their effective values. A 2000-volt alternator produces an e.m.f. which varies between limits of 2828 (2000 × 1.414) volts acting one way to 2828, acting the other way in a circuit to which it is connected.

111. Effective Current which Flows due to Given E.m.f.—When it comes to calculating the amount of current which flows in an A.C. circuit Ohm's law, so useful for D.C. circuits, will not hold good. A law which corresponds with it and which does hold true is the following one:

$$I = \frac{E}{Z}$$

I is effective current in amperes
E is effective e.m.f. in volts
Z is impedance in ohms.

The impedance of a circuit to alternating current is more than the resistance of that circuit to direct current. Sometimes it is very much more. Impedance cannot be calculated by any such simple methods as have been shown for calculating resistance. There will be more to explain about it later; in the meantime it may be used in connection with E and I exactly as resistance in a D.C. circuit. No space will therefore be taken here to illustrate in detail how to use it in calculations; only two or three simple examples will be given.

1. A certain circuit has an impedance of 22 ohms. How many volts A.C. must be generated in it to send 5 amp. of A.C. through it?

$$E = IZ \qquad\qquad E = 5 \times 22 = 110 \text{ volts}$$

2. In a certain circuit shown in Fig. 138, a difference of potential of 36 volts is found between *a* and *b*. A current of 9 amp. of A.C. is flowing through the circuit. How much impedance has this part of the circuit?

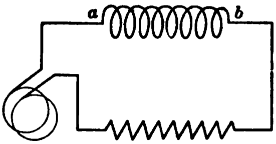


FIG. 138.

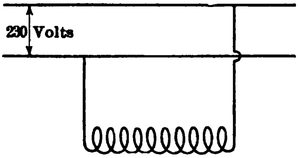


FIG. 139.

$$Z = \frac{E}{I} \qquad\qquad Z = \frac{36}{9} = 4 \text{ ohms}$$

3. Across an A.C. line at constant potential of 230 volts, Fig. 139, I expect to connect a piece of apparatus having an impedance of 11.5 ohms. For D.C. it has a resistance of 5 ohms. How much current will flow?

$$I = \frac{230}{11.5} = 20 \text{ amp.}$$

112. Another Method of Representing I and E.—From what has already been stated in connection with Fig. 134 and noting the way it was marked, as well as from various applications already made, it will be plain that in Fig. 140, *a* represents a current of 5 amp. flowing one way and *b* a current of 5 amp. flowing the other way. The direction the line is drawn (from 0 to the arrow point) has a significance as well as the length of line. Thinking of current in an A.C. circuit *a* may represent the maximum value of a current when flowing one way and *b* the maximum value when flowing the other way; that is, the two lines represent maximum values of current differing in phase by a half period. Such representation of current by lines is so convenient that it is desirable to have a method of representing intermediate values as well. The plan which is made use of places lines at different inclinations to represent current at other intermediate phases. Thus in Fig. 141 line *Oa* is the line *a* of Fig. 140 repeated. *Ob*, *Oc*, *Od*, *Oe*, all lines of the same length as *a* (5 units long) represent current in other phases. The phase to which each of these inclined lines corresponds may be settled by noting a construction method shown in Fig. 142. The curve of current is shown at the right. Fig. 141 is reproduced at the left. As *Oa* corresponds with *II* so

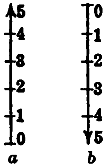


FIG. 140.

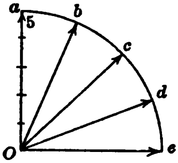


FIG. 141.

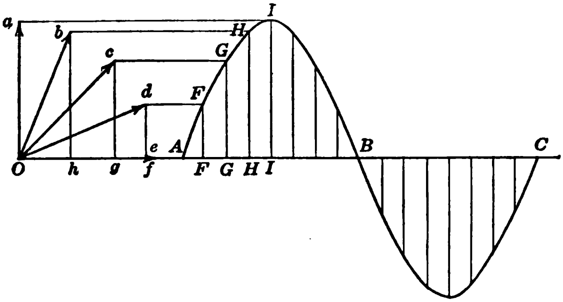


FIG. 142.

hb is the same as *HH*. *Ob* therefore represents *HH*. In like manner *Oc* stands for *GG*, *Od*, for *FF* and *Oe* for no current at all (point *A*). It is important to notice that just as the curve of current *ABC* represents an alternating current having maximum value of 5 amp. *at any frequency* (for no time is marked on the base line and any could be put there) so the inclined lines of Fig. 141 represent different phases of an alternating current without regard to the frequency of the current.

It is very easy to become used to this method of representation for alternating currents and e.m.fs. Thus in Fig. 143, *OA* is a current which has a maximum value of 4 amp., just now past zero value and coming to maximum. This can be seen without an arrow point on the line since when two lines join like *OA* and *OB* it is assumed unless specially marked, that they are drawn out from *O*. But since it is much more convenient to talk of currents by effective values rather than maximum values, and a simple ratio connects them it is very usual to plot effective values in these line diagrams, where maximum values should be found. Hence in Fig. 143, *OA* would commonly stand for a current of 4 amp. effective value, rising to maximum in a certain direction while *OB* is a current of 5 amp. effective value flowing the opposite way which has just passed its maximum value and is diminishing in amount. In like fashion *OC* and *OD* are equal currents. *OD* is lagging in phase ¼ period behind *OC*, *OC* having passed maximum, and *OD* is approaching maximum, both flowing the same way.

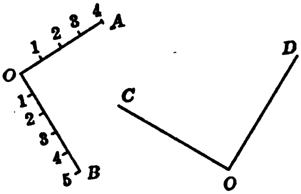


FIG. 143.

113. Difference of Phase as an Angle.—Referring once more to Fig. 141 since a line must stand at every possible position through 360° to represent all values an alternating current may have, it is convenient to think of the line with regard to its angular position, and speak of phase and difference of phase in degrees. If the line representing the current is placed in every possible position each of the current values represented in the curve of A.C. in Fig. 144 has been represented. If then the whole cycle is represented from 0° position of the line to 360°, we may mark off degree values on the current curve if we choose (shown in Fig. 144). This has the advantage that we can refer with exactness to currents in certain phase, without involving an idea of frequency or how fast the current changed from one phase to another. Thus we say a current has advanced through 180° of phase and mean it has an exactly corresponding value but directed the other way in the circuit; or we speak of one current *OD* lagging behind another *OC* by 90° of phase (see Fig. 143) and in neither case is any idea of frequency involved. In Fig. 144 we think of *Oe′* as representing a later condition of *Oe* and we speak of it having a phase difference of 30° with it.

Figures in which lines stand for e.m.fs. and currents, are called clock diagrams. By inspection of them, noting the relation of the line considered to a horizontal line, one can see in what phase is each quantity represented. We can also see what differences in phase exist and what is their relative magnitude. For reasons already explained the effective values of current and e.m.f. are plotted in clock diagrams and whenever more than a single line is used the arrow point to designate where the line ends is omitted.

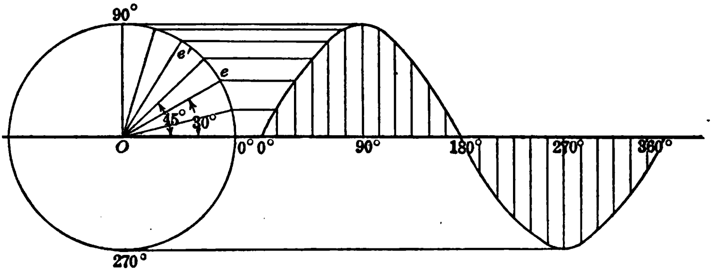


Fig. 144.

114. Circuit E.m.f. and Applied E.m.f.—In an A.C. circuit, current only flows because e.m.f. sends it. The e.m.f. which sends the current is called the circuit e.m.f. It has a maximum value at the same time that current is a maximum; zero value when current is zero; it is always in phase with the current. Fig. 145 shows a current of 40 amp. (maximum value 56.4 amp.) sent by an e.m.f. of 100 volts (maximum value 141 volts). On the left they are shown as curves and on the right as lines. On the right they are both shown halfway in phase between zero and maximum; the arrow points marking the end of each line (both start at 0).

The circuit e.m.f. simply gets the current through the resistance of the circuit. It is IR where I = amperes, R = ohms, IR = volts.

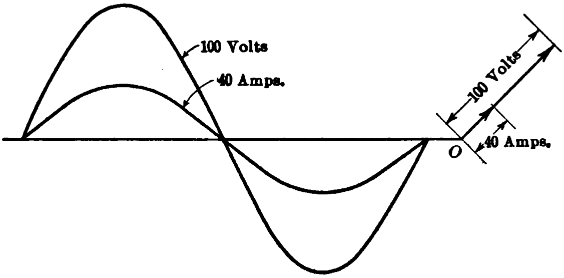


Fig. 145.

In most circuits the applied e.m.f. and the circuit e.m.f. are different. To illustrate this a problem may be used.

Across a 115-volt line a piece of apparatus is connected whose resistance is 15 ohms. A current of 5 amp. is found to flow. What is the circuit e.m.f. for this piece of apparatus and why does no more current flow?

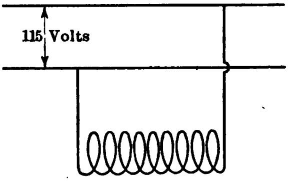


Fig. 146.

Circuit e.m.f. = $IR = 5 \times 15 =$ 75 volts.

No more current flows because the impedance is more than the resistance

$$Z = \frac{E}{I} \qquad Z = \frac{115}{5} = 23 \text{ ohms.}$$

The applied e.m.f. in this case is that which the line supplies. Were two things in series connected across the circuit, the applied e.m.f. to one would be that part of the line voltage which reaches it; what a voltmeter connected across its terminals would read. Or again if referring to a *whole* circuit the applied e.m.f. is that generated by the alternator. The reason for the difference between the applied and circuit e.m.f. is to be found in the fact that there is another e.m.f. in the circuit; a self-induced e.m.f. due to the varying current there.

This may be more fully understood if the condition of affairs existing in a D.C. circuit in which a motor is operating is called to mind. The current is sent through the motor's resistance by a few volts whose value is *IR*. Should the question be asked "Why is it that when the motor has only a resistance of an ohm or less, 110 volts sends but a few amperes?" The answer is "Because there is another e.m.f. in the circuit; the motor e.m.f." The e.m.f. which sends the current (it might be called the circuit e.m.f.) is the difference between the applied and motor e.m.f.s.

115. Inductance.—By the inductance of a coil or circuit is meant the property it has such that a change of current through it sets up an e.m.f. in it. Every coil or circuit has this property. Consider an example. In Fig. 147 is shown a coil of three turns. When current flows in the coil, flux passes through it. When the current varies the flux varies. This will produce an e.m.f. in the coil (section 106); an e.m.f. of self-induction. Hence the coil has inductance. If the number of turns of coil were doubled the flux through the coil is doubled for the same current; and if the current is varied at the same rate as before, twice the e.m.f. will be generated in each turn, and so the coil has four times the e.m.f. in it; or the inductance is increased four times as the result of doubling the turns. If iron is put in the path of the flux, the flux would be increased, and with current varying at the same rate the e.m.f. of inductance is increased. Hence the inductance is increased. From this we see that the inductance of a circuit, or a piece of apparatus is as definite a property as its resistance. In D.C. work it is usually of no consequence because current is steady and the property of inductance is only shown by the e.m.f. which is generated while current is changing. The inductance of any piece of apparatus or of a circuit depends upon and is regulated by the number of turns of coil or circuit and the amount of flux per ampere which passes through it.

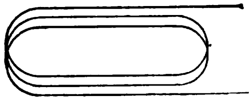


Fig. 147.

116. E.m.f. of Inductance in an A.C. Circuit.—The amount of the e.m.f. of inductance produced in a coil (a simple circuit is a coil of one turn) depends not only on the inductance of the coil but also on the rate at which the current varies. This in turn depends partly on how large the current is which changes, and partly on how fast it changes. Limiting the statements here to those which apply to alternating current let us consider certain facts regarding the e.m.f. of inductance which is generated in an A.C. circuit. In Fig. 148 is shown a current of 3.53 amp. (effective value) whose maximum is 5 amp. At the zero value of current a space is laid off marking 2/1000 sec.; the time from 1/1000 before zero to 1/1000 after zero. Very careful measurements will show that in this time current drops from 0.261 to 0 and on to 0.261 amp. the other way. This means that there is a *change* of 0.522 amp. in 2/1000 sec. or at the rate of 261 amp. per second. On each side of maximum value 1/1000 sec. is laid off for a 2/1000 sec. interval. Careful measurements would show that in this time current rises from 4.99 to 5 and drops again to 4.99 amp. This is a change of

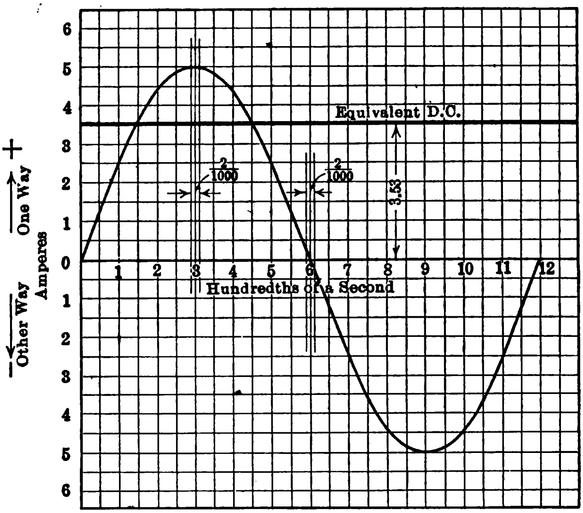


FIG. 148.

0.02 amp. in this time interval which is very small compared with the change per second as the current passes through zero value. But further, if the time limits are made still shorter, the current curve included between the lines marking the interval considered at maximum value would be flat; or the current would not be changing at all. From this we see that when an alternating current is at maximum, its rate of variation is zero and when it is at zero its rate of variation is a maximum. Simple observation of the slope of the curve representing the current shows this; if the current curve is horizontal, just then the current is having no variation; if very steep there is a high rate of variation. The varying current produces a varying flux through any coil or loop, which by its rate of variation sets up an e.m.f. of inductance in the coil. This flux has a rate of variation the same as that of the current which produces it for the flux is due to the current. Hence we reach the conclusion that in an A.C. circuit not only is an e.m.f. of self-inductance present, but it has its biggest value when the current passes through zero; while it is down to zero (does not exist) when the current is maximum. It therefore has zero, maximum, and intermediate values; it is alternating; it has the same frequency as the current.

Looking again at the figure it is easy to see that if the current had been larger the frequency remaining the same, the e.m.f. of inductance due to it would be larger because the rate at which the current varies would have been larger. Again had the frequency been twice as great (half as much time per cycle) the current at any instant would have been changing twice as fast and so the e.m.f. of inductance would have been doubled. In a clock diagram, if the current line is vertical the rate of variation of current is zero; while when the line is horizontal the rate of variation is a maximum. The e.m.f. of inductance is alternating and so has a place in the clock diagram.

117. Phase Relations between Current and E.m.f. of Inductance.—In Fig. 149, *OI* represents an alternating current flowing through a coil. The vertical and horizontal lines are lines of reference. Then since the e.m.f. of inductance which this current sets up is alternating and reaches zero value when the current is maximum and maximum value the current is zero, either *OL* or

OL' must represent it. Now when the current is rising the e.m.f. induced is in such a direction as to oppose the change in current and is directed against the flow of current (see section106); that is, directed the other way in the circuit. Hence *OL* must be the proper line to represent it, for it is below the horizontal line of reference while the current line is above. They are, therefore, in opposite directions in the circuit. The e.m.f. of inductance is therefore an alternating e.m.f. which lags in phase ¼ period or 90° behind the current. This relation is fixed.

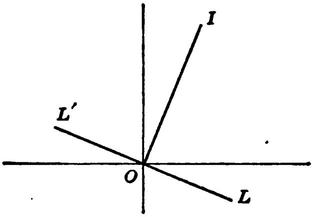


Fig. 149.

118. Resultant E.m.f. when Two Act in the Same Circuit.—If we have two e.m.fs. in the same circuit it is clear that at any instant the total e.m.f., if they are directed the same way, will be their sum, the direction of the resultant being that of either one; if they are directed against each other the resultant is their difference, the direction of the resultant being that of the larger.

In Fig. 150 an alternating e.m.f. *abcd*, maximum value 30 volts, is plotted, and another e.m.f. *efgh*, maximum value 50 volts, lagging 60° behind it. We assume they are in series in the same circuit. Applying the principle just stated the curve of resultant e.m.f. *ABCD* is secured. This may be seen as follows: At the instant marked 1 the 30-volt e.m.f. has reached 25.9 volts; the other is passing through zero, hence the resultant at that instant is 25.9, or at 60° the curves *abcd* and *ABCD* cross.

Instant marked	Value of 30-volt e.m.f.	Value of 50-volt e.m.f.	Sum of col. 2 and 3; value of resultant
1	25.9	0	25.9
2	30	25	55
3	25.9	43.3	69.2
4	15	50	65
5	0	43.3	43.3
6	−15	25	10
7	−25.9	0	−25.9
8	−30	−25	−55

The table shows how values along the curve *ABCD* are made from instantaneous values of the other curves. We may note that the resultant curve passes maximum at a point between 3 and 4, it is in fact at 128.2°, where it is 70 volts. So also the resultant passes through zero when the diminishing value of the 30-volt e.m.f. is just equal and opposite to that of the 50-volt e.m.f. This is at 218.2° at the position marked *C*. The resultant e.m.f. has the same form as the ones from which it is made up and is intermediate in phase between the other two. It lags 38.2° behind the 30-volt e.m.f. and leads the other one 21.8°.

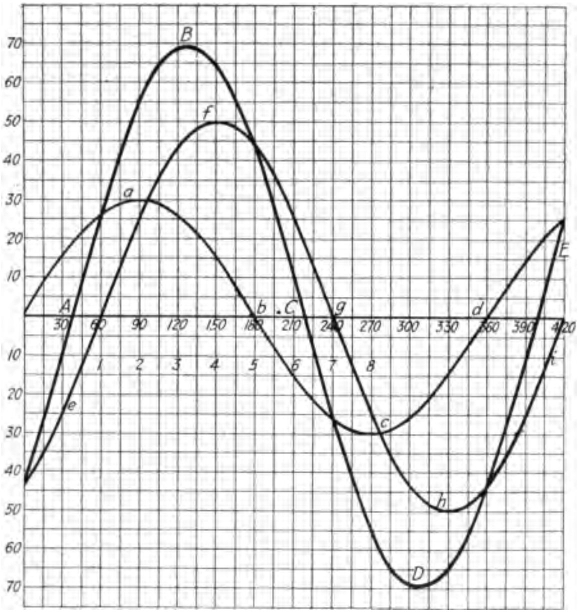


Fig. 150.

The effective value of the 30-volt e.m.f. is 21.21 volts; of the 50-volt e.m.f. it is 35.35 volts. The effective value of the resultant is 49.49 volts. Hence the result of having 21.21 volts A.C. in series with 35.35 volts with a phase difference of 60° between them is to have 49.49 volts in the circuit, which is considerably less than their arithmetic sum.

The same result can be arrived at in a very much simpler and quicker way by plotting the e.m.fs. as lines in a clock diagram with the proper phase difference, and then by a construction shown in Fig. 151 the resultant can be found. All the phase relations come out at once also. If in some practical problem for which effective values were given the same methods were used, the resultant found would be the effective value, for to pass from maximum values to effective in every case the values in the figure are multiplied by 0.707. Fig. 152 is made to show how the two methods of finding the resultant are equivalent. The clock diagram is drawn so as to show all three e.m.fs. properly placed for position 2 when e.m.f. *abcd* is at maximum.

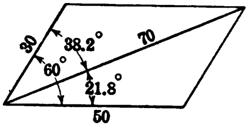


Fig. 151.

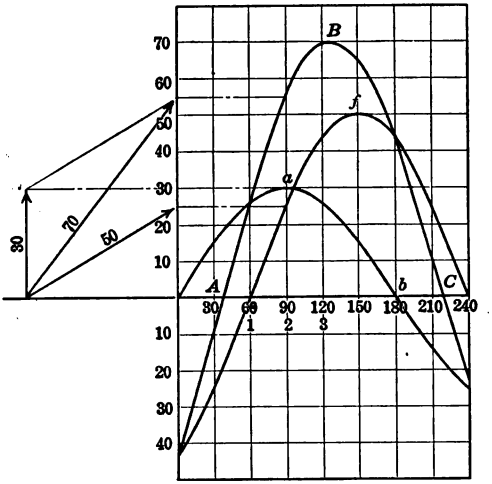


Fig. 152.

Nothing need be said to explain how much simpler it is to find a resultant e.m.f. by using straight lines for each than by the other plan. Furthermore, by a look at Fig. 151 it will be clear that the resultant e.m.f. will vary according to the phase difference between the e.m.fs. If two e.m.fs. are in series, one of 100 effective volts and the other 80, the resultant will be 180 if they are in the same phase, diminishing with increased phase difference until at last when in opposite phase the resultant will be but 20 volts.

119. Relations between Applied E.m.f., Current, Etc.—An application for the principle stated in the last section may be found in interrelating the applied e.m.f., the e.m.f. of inductance, and the circuit e.m.f. in an A.C. circuit. Just as in a D.C. motor circuit the applied e.m.f. may be thought of as in two parts, one "held up" by the motor e.m.f. and the other sending the current through the resistance, so in any A.C. circuit the applied e.m.f. has two parts, one is "held up" by the e.m.f. of inductance while the remaining part (the circuit e.m.f.) sends the current. In Fig. 153 some e.m.fs. are plotted. The vertical and horizontal lines are lines of reference. *OC* and *OL′* are two e.m.fs. which together make the applied e.m.f. *OE*; or *OE* is an e.m.f. which is made up of two parts, *OC* and *OL′*. Now in the figure *OE* is drawn to represent the alternating e.m.f. applied to a piece of apparatus. The two parts into which it is divided are then *OL′*, that part which holds up the e.m.f. of inductance *OL*, and the part *OC* which gets the current through the resistance. In order that *OL* shall be

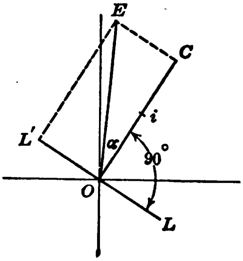


FIG. 153.

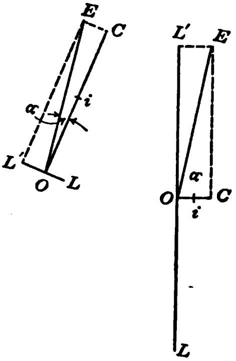


FIG. 154.

"held up," *OL′* must be equal and opposite to it as shown. If *OC* is the circuit e.m.f. it is in phase with the current in the circuit (see section 114 and Fig. 145). With these things in mind it is clear that the figure must be correctly drawn. The e.m.f. of inductance lags 90° behind the current as marked; hence the other lines must fall into the relations shown. We find that in such a circuit the current lags behind the applied e.m.f., a matter of great importance often to be referred to later. This phase relation is so important that Fig. 154 is drawn to show at the left hand conditions in a circuit when the e.m.f. of inductance there is quite small, while at the right hand the conditions are shown when the e.m.f. of inductance has become quite large. In these figures the applied e.m.f. has been kept of the same magnitude as in Fig. 153 and in all three the angle by which the current lags behind the applied e.m.f. is marked with the same letter, α.[1] The current lags more as the e.m.f. of inductance is increased, while the circuit e.m.f. and also the current decrease. If the resistance of the apparatus is 2 ohms, for example, the current is represented in each case by the length of the line from *O* to *i*. The current always equals the circuit e.m.f. divided by the resistance and for this case is therefore half the length of the circuit e.m.f. line.

Increasing the e.m.f. of inductance indefinitely will eventually decrease the current almost to nothing and increase the current lag to almost 90°. The e.m.f. of inductance can never be quite as large as the dynamo e.m.f., but in important apparatus it comes to be practically as much as this.

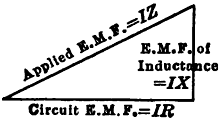


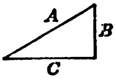
FIG. 155.

120. Impedance and Reactance.—From Fig. 153 we may obtain a set of lines forming the triangle of Fig. 155. This triangle is much used in connection with A.C. problems. The sides are always placed in the relation shown, the circuit e.m.f. being placed horizontally.[2]

---

[1] A letter of the Greek alphabet pronounced "alpha".

[2] This is a right-angled triangle. The side 1*Z* is the hypothenuse; the other two sides form a right angle between them. For any right-angled triangle if we call the sides *A*, *B*, *C* this relation holds



$$A^2 = B^2 + C^2$$

This is frequently used in what follows.

Now the applied e.m.f. = IZ, and the circuit e.m.f. = IR; hence the inductance e.m.f. should = IX. X is called the reactance of a circuit or of a piece of apparatus. It is measured in ohms. It is due to the inductance but varies directly with the frequency because the inductance e.m.f. so varies.

Thus suppose a certain circuit has a resistance of 20 ohms, and when 110 volts are applied a current of 5 amp. flows. What is the e.m.f. of inductance and the reactance of the circuit?

The circuit e.m.f. is $20 \times 5 = 100$ volts. Knowing the hypothenuse and one side of a right-angled triangle we can find the other:

$$\begin{aligned} 110^2 &= 12{,}100 \\ 100^2 &= 10{,}000 \\ \hline \text{difference} &= 2{,}100 \end{aligned}$$

$$\sqrt{2100} = 45.83 \text{ volts e.m.f. of inductance.}$$

To find the reactance:

$$\begin{aligned} IX &= 45.83 \text{ volts} \\ \text{since } I &= 5 \\ X &= \frac{45.83}{5} \\ X &= 9.16 \text{ ohms reactance.} \end{aligned}$$

In order to make this matter of reactance more clear an example may be borrowed from D.C. motor work and a problem worked as follows:

A motor has a resistance of 2 ohms. When 110 D.C. volts are applied, a current of 5 amp. flows.

The circuit e.m.f. (volts to get current through the circuit) is $2 \times 5 = 10$ volts. This leaves 100 volts motor e.m.f. and this is spent as though $^{100}\!/_5 = 20$ ohms were in the circuit.

There is a certain resemblance between this 20 ohms and the 9.16 ohms derived above. The real thing is the e.m.f. of inductance. This only shows itself because of a certain property of a circuit, its inductance, described in section 115. The reactance is a sort of resistance which the inductance brings into the circuit.

Since I is a factor in each of the e.m.fs. forming the sides of the triangle of Fig. 155, another triangle may be constructed, as in Fig. 156. A current of 2 amp. has been assumed. Hence dividing each side of the triangle of Fig. 155 by 2 (halving it) we get Fig. 156. Here we find what impedance really is. It is the total resistance to the flow of current in an A.C. circuit and is made up of two parts, resistance and reactance, which must be combined in a right-angled triangle relation to make it. From this triangle we have

$$Z = \sqrt{R^2 + X^2}$$

and so

$$I = \frac{E}{Z} = \frac{E}{\sqrt{R^2 + X^2}}$$

Looking at this last formula we see that if a circuit has reactance so small as to be of no account, the impedance for alternating currents is the same as the resistance; that is, Ohm's law is true. The current flowing would also be in phase with the applied e.m.f., for in Fig. 155 the line for e.m.f. of inductance would then have become so short that it need not be counted. On the other hand, if the resistance is too small to count in comparison with the reactance a very different condition of affairs holds good. The reactance then regulates the amount of current, and it lags 90° or a quarter period behind the applied e.m.f.

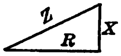


Fig. 156.

121. Alternating-current Power.—If the power in a D.C. circuit is to be determined, a simultaneous measurement of volts applied and current flowing is made; the product is the power used just then. If the power were fluctuating, a number of simultaneous readings of volts and amperes would be made, and an average of the products taken to give the continuous supply of power during the time under consideration. The same principle holds for an A.C. circuit; the product of applied volts by current flowing at that instant gives the power transformed at that instant. If, therefore, we have plots of e.m.f. and current for a given case, we may calculate the power at successive instants by taking a number of products of volts and amperes. In Fig. 157 this has been done for a case where 100 volts are sending 200 amp. (both effective values) through a circuit, the amperes being in phase with the volts. The values found by the calculation have been plotted in a power curve. At a couple of points the values may be noted. Thus at the instant *a* when the applied e.m.f. has reached a phase corresponding to 30° there are 70.7 volts acting and 141.4 amp. flowing. The product is 10,000 watts. At instant *b* when *E* and *I* are at maximum there are 141.4 volts and 282.18 amp.; hence 40,000 watts transformed. Noting then the whole power curve we see that the power goes through great fluctuations, in this case rising from zero to maximum with increasing volts and amperes and dropping again to nothing every half cycle. The power transformed, that which we speak of as the continuous expenditure, is the average of all the values or the average height of the power curve. When this is calculated it turns out to be 20,000 watts, that is, the height of the line *XY* drawn in this figure.

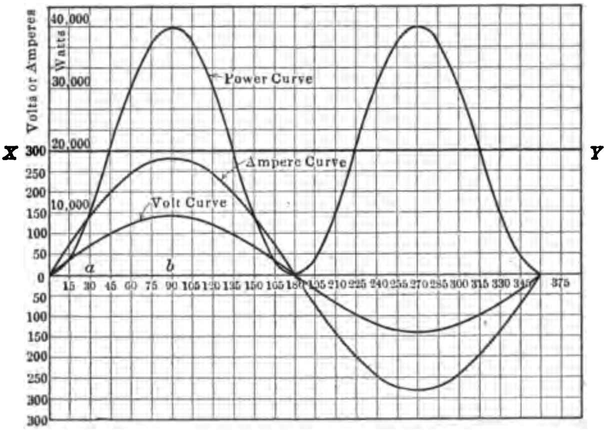


Fig. 157.

But when current and e.m.f. are not in phase a different result is reached. In Fig. 158 the same volts and amperes as before are plotted, but now the current lags 30°. Looking over the curves we see that there are times when the volts are directed one way and the current the other. During such intervals the power transformation is reversed, for instead of dynamo conditions we have those which are distinctive of motors. Hence when we get values and plot a power curve this has loops below the zero line;

positive values mean power transformed into the circuit (dynamo operation), and negative values power transformed out of it

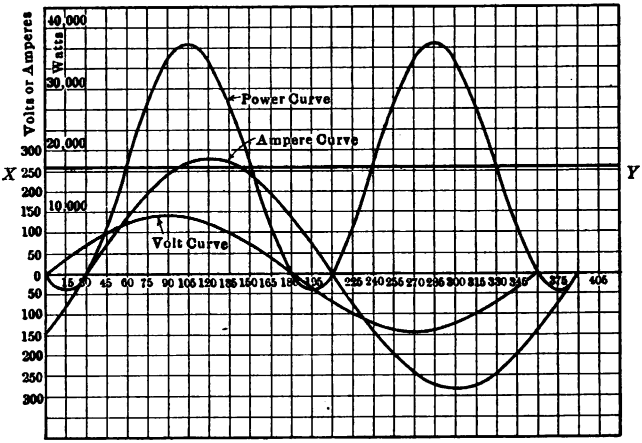


FIG. 158.

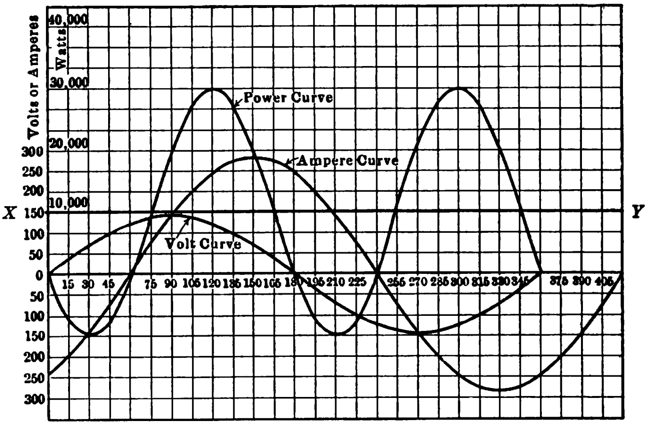


FIG. 159.

(motor operation). Numerically some calculated values would be:

Phase of E	Value of E	Value of I	Product or watts
0°	0	141.4	0
30°	70.7	0	0
60°	122.5	141.4	17,315
90°	141.4	245	34,630

The maximum value of the curve is less than before, and there is a loop below the zero line; hence the average power as shown by line XY is considerably less than before, 17,320 watts, although the volts acting and current flowing are the same as before. Fig. 159 shows the same thing but with current lagging 60°. The power transformed now is only 10,000 watts. We see, therefore, that the power transformed in any A.C. circuit cannot be calculated except by taking account in some way of a property of the circuit which causes a lag of current and determines its amount. We could not expect that the power used in A.C. apparatus would be the product of a voltmeter reading by an ammeter reading, partly because of the special significance of these readings and also because they are quite independent of the phase relations between e.m.f. and current. The product of volts by amperes (effective values) is the apparent power; their product multiplied by a proper number, the power factor, gives the real power. In common usage

$$\frac{\text{amperes} \times \text{volts}}{1000} = \text{kilovolt-amperes or kv.a.}$$

$$\frac{\text{amperes} \times \text{volts} \times \text{power factor}}{1000} = \text{kilowatts or kw.}$$

Alternating-current power is generally measured directly by a wattmeter.

122. Power Factor. Wattless Current.—The power factor of a circuit, coil, or piece of apparatus may be defined as the number by which the apparent power is multiplied to get the real power. It can never be a number larger than 1 and may be anything from that down to 0, for referring to curves and data of the last section it will be noted that if the current were to lag 90° the power loop above the zero line of reference would be just as large as the loop below. Under such conditions the power which is transformed into the circuit is immediately afterward transformed back again, or there is no real permanent power transformation. That is, the apparent power, 20,000 watts, must be multiplied by 0 as the power factor to get its real value. Power factors in practical apparatus under working conditions are not often less than 0.5, while for most circuits the power factor will be 0.9 or more.

Investigation shows that if the product of the applied volts (read on a voltmeter connected to terminals) by the amperes flowing (read on an ammeter in the circuit) is multiplied by the ratio of the circuit e.m.f. to the applied e.m.f., the real average power is determined. Hence

$$\text{power factor} = \frac{\text{circuit e.m.f.}}{\text{applied e.m.f.}} = \frac{IR}{IZ} = \frac{R}{Z}$$

The power factor of any circuit or coil is determined by taking the ratio of its resistance to its impedance.[1]

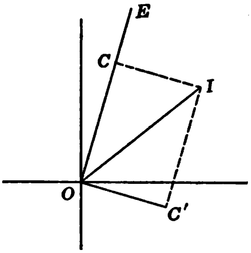


Fig. 160.

In considering the power spent in an A.C. circuit the current is often thought of as made of two components. One is the amount of current in phase with the applied e.m.f., which when multiplied by this e.m.f. would show the power expenditure which really occurs. This is the actual current multiplied by the power factor and is called the working current. The other component is that part which is lagging 90° behind the applied e.m.f. It is called the wattless current. This, with the working current, makes the actual current flowing. In Fig. 160, *OE* is the applied e.m.f.; *OI* the current in the circuit; *OC* is the working current, and *OC′* the wattless current.

To determine the angle of lag of the current behind the applied e.m.f., one may determine the impedance and the resistance of the circuit or pieces of apparatus and then proceed as follows: Draw the impedance *Z* as shown in Fig. 161. On this line as a diameter draw a semicircle. Draw in the resistance as a chord, as shown. The angle between Z and R, as marked, is the angle sought. Refer to Fig. 156 in this connection. It should be noted that since the angle of lag is determined by fixed properties of a circuit, the angle of lag of current and the power factor of the circuit are fixed for it whether current is flowing or not, and independent of the amount flowing.

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[1] This must not be taken too literally when applied to motors in operation.

123. Apparatus in Series and in Parallel.—On account of the way in which lag of current behind applied e.m.f. involves a relation between resistance and impedance, if we put two pieces of apparatus in series the lag of current flowing through one behind its applied e.m.f. may be quite different from that in the other. Hence the sum of the e.m.fs. applied to each would not be the e.m.f. applied to the circuit made of both together in series. In the same way and for a corresponding reason, the sum of the impedances in a circuit is not the impedance of a circuit. The power factor of a piece of apparatus in a circuit may be very different from the power factor of the circuit in which it is being used. The sum of the separate reactances of the parts of a series circuit, however, is always the total reactance, just as the sum of the separate resistances is the total resistance. Using this the combined impedance of devices in series can be determined.

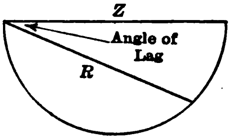


Fig. 161.

When a circuit has branches with devices in parallel, the total current flowing in the mains is generally less than the sum of the currents in the branches. It is always true that the sum of the working currents in the branches is the total working current and the sum of the wattless currents the total wattless current. If the total value of wattless and working currents separately are known the actual current can be determined by combining them, using the method of Fig. 160.

If the impedance of a circuit or device is known this holds only for a certain frequency. With change in frequency the impedance changes, but not proportionately. The resistance always stays constant. The power factor also changes with change of frequency.

QUESTIONS AND PROBLEMS

1. An alternating current rises from zero to maximum in 1/100 sec. How many alternations in a minute? What is the period of this current? What is its frequency?

2. A certain A.C. has completed 18,000 cycles in 6 min. What is its frequency? What frequency if it completed 7500 cycles in 2½ min.? What frequency would we find if 16,000 cycles were completed in 2 min.?

3. A certain A.C. makes 15,000 alternations per minute. What is the frequency of the current? What is its period? How many cycles completed in 10 sec.? How long to rise from zero to maximum?

4. Draw a figure similar to Fig. 134 representing a current with maximum value of 10 amp., and then mark the time in seconds properly for an alternating current having a frequency of 30. Plot another on the same diagram of 5 amp. maximum, having the same frequency but lagging ¼ period behind it.

5. An A.C. (*A*) has reached maximum value in a certain direction. Another (*B*) is just passing through zero and will rise, flowing in the same direction. How do they differ in phase? How would it be if *A* is halfway (in time) between zero and maximum decreasing and in a certain direction, while *B* is halfway between zero and maximum increasing the other way?

6. An A.C. (*A*) lags a quarter period behind another (*B*). Make a statement of the phase of *B* if *A* is past maximum decreasing, and quarter of the time between maximum and zero has elapsed. Restate for *B* if *A* leads *B* ¾ period.

7. A direct current of 15 amp. is passed through a certain fuse wire which just melts it off. How much A.C. will just melt it? What would be the largest and what the smallest value of this current? What should its frequency be?

8. A certain electric laundry iron is heated to 250° by the passage of 5 A.C. amp. through it continuously. The frequency of this current is 60. How much D.C. passed through it will produce the same rise in temperature? If the A.C. were raised to 6 amp., how would the heat delivered to the iron compare with what it was before?

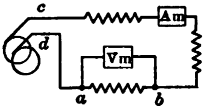
9. If an alternator supplies 2200 volts to a circuit, what is its maximum value? If the maximum value of the current it sends is 70.7 amp., what is the value by which we call it?

10. Plot an e.m.f. of 100 volts as a line (scale ¼ in. = 10 volts) which is just now halfway in phase between zero and maximum (rising in value) and another of 80 volts lagging ¼ period behind it. Show the same e.m.fs. by a plot of A.C. curves.

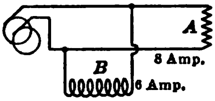
11. In an A.C. 60-cycle circuit an e.m.f. of 104 volts is in use. Upon measurement, the current flowing is found to be 8 amp. What is the impedance of the circuit? To cut the current down to 2 amp., what must the impedance be made?

12. The impedance of a certain circuit is 75 ohms. How much current will an alternating e.m.f. of 225 volts (60 cycles) send through it? How much if the e.m.f. is raised to 300 volts.

13. The voltmeter in the circuit shown reads 30 volts. The ammeter reads 20 amp. What impedance from *a* to *b*? If terminal volts *c* to *d* are 500, what is the impedance of the circuit?



14. Two e.m.fs. are in series in an A.C. circuit and differ in phase by 180°. One is 100 volts and the other 90 volts. Plot them as lines in a diagram and decide how many volts from a single source might replace them both so the same flow of current in the circuit would result. How would it be if they were in the same phase?



15. In this circuit the current in branch *B* lags behind that in *A* by 90°. How much current flows from the dynamo to supply both branches? (Draw a diagram and measure if you cannot calculate it.)

16. Would any considerable self-induced e.m.f. be found in an A.C. circuit made up of line and incandescent lamps on it connected in parallel? How for one with line and motors in parallel? Why in each case?

17. An A.C. dynamo supplying 200 volts at its terminals has a piece of apparatus connected across its terminals known to have a resistance of 16 ohms. A current of 10 amp. is flowing. Find the impedance of the circuit and the number of volts of self-induced e.m.f. there.

18. An A.C. motor has a resistance of 7 ohms and a reactance at 60 cycles of 7 ohms. 10 amp. is flowing through it. Find the applied e.m.f., the self-induced e.m.f., and the circuit e.m.f.

19. A coil used in a certain A.C. circuit has a resistance of 3 ohms. The current flowing in it is 10 amp. but the applied e.m.f. measures 50 volts. State the cause. Find the reactance of the coil.

20. (*a*) A certain piece of apparatus has a resistance of 40 ohms and a reactance of 2 ohms. How many volts are required to send 3 amp. through it? Construct a clock diagram to show phase relation of current and applied e.m.f.

(*b*) Another piece of apparatus has a resistance of 2 ohms and a reactance of 40 ohms. How many volts required to send 3 amp. through it? Construct a clock diagram to show phase relation of current and applied e.m.f.

21. An A.C. dynamo is rated at 200 kv.a. at 500 volts. Calculate the full-load current and the kilowatts for full-load current on a circuit having a power factor of 0.9.

22. An alternating-current arc lamp burning at 60 cycles on a constant-potential 105-volt circuit has a power factor of 0.7. 7 amp. are flowing through it. How many watts is it using?

23. A certain single-phase A.C. motor marked 4 hp. is to be connected to a 200-volt line. It has an efficiency of 80 per cent. At full load it has a power factor of 0.8. What current flows through it at full load?

24. Calculate the power factor for and the power used in each piece of apparatus described in question 20.

CHAPTER XI

ALTERNATING-CURRENT TRANSFORMERS

124. Purpose of a Transformer.—In a later chapter it will be shown that when electric power is to be transmitted with a given percentage loss, a very great advantage results from the use of high voltage. If a higher voltage is used, a higher resistance line is correct; not only proportionately higher but in proportion to the square of the voltage used. Thus if 1100 volts is used to transmit power rather than 110, the line resistance is made 100 times as much. For according to the principle stated 10 times as many volts are used and $10^2 = 100$. Making the resistance 100 times as much for the same transmission distance would make the required cross-section $1/100$ as great and so the weight and cost of copper only $1/100$ as much.[1] But electric power at high voltage has little use commercially. It is dangerous to handle, lights cannot be made to use satisfactorily with it, and other apparatus using but a small amount of power is so expensive to make as to be impractical. Hence if the benefits of high voltage of transmission are to be combined with those of low voltage for the user, some apparatus is necessary which not only can make the transformation but which can do this at any customer's premises and do it automatically without requiring any attention.

A transformer is such a piece of apparatus. Without it most of the engineering advantage in the use of alternating current would be lost. A transformer may be used equally well to receive energy at high voltage and deliver it at low, when it is a lowering or "step-down" transformer, or to receive energy at low and deliver it at high voltage, when it is a raising or "step-up" transformer. The same transformer will operate either way, transforming from high to low, or low to high voltage.

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[1] Referred to again in section 228.

125. Form and Construction.—A transformer consists fundamentally of two coils of insulated wire having no electrical connection with each other, so placed that the flux produced by the flow of current in one will pass through the other. As a means of increasing and directing the flux in practical apparatus both coils are wound on the same iron core. Fig. 162 shows them; each subdivided into two equal parts.

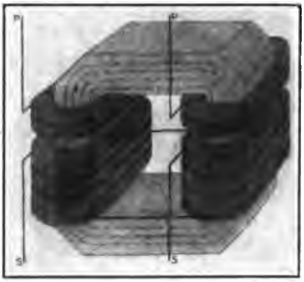


FIG. 162.

Transformers are made with open magnetic circuits or with closed magnetic circuits. A transformer with an open magnetic circuit is one whose flux path is partly through air. Nearly all transformers are built with closed magnetic circuits. They may be of the shell or core type. The arrangement of the shell type is shown in Fig. 164, that of the core type is in Fig. 163. In either case it is hard to distinguish the separate coils; hence in Figs. 162 and 165 are shown the equivalent arrangements in a more satisfactory way. One coil has terminals marked *PP* and the other *SS*. In the actual transformer the coils are very carefully insulated from each other and yet are so placed, even by subdivisions of either or both coils, so that all the flux which goes through one must go through the other. In Fig. 166 is shown the conventional diagram regularly used to represent a transformer.

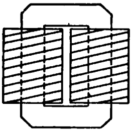


FIG. 163.

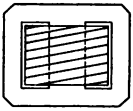


FIG. 164.

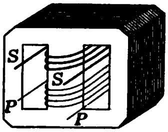


FIG. 165.

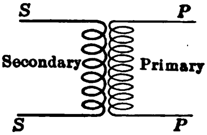


FIG. 166.

It will be noted in the figures that one winding is intended to be shown by a coil of many turns of fine wire and the other by one having fewer turns of coarse wire. Since a transformer transforms electrical energy at high voltage to electrical energy at low or *vice* *versa*, it must hold true that a step-up transformer which receives a large current at a low e.m.f., delivers a small current at high e.m.f. This in part explains the size of wire found in each winding; it being proportioned to the current it must carry.

The winding into which current is introduced is called the primary and that from which current is taken the secondary. Step-down transformers are so very common that it is a common but dangerous practice to call the fine wire winding (*PP* of the figures) the primary and the coarse wire winding (*SS* of the figures) the secondary.

The iron cores of transformers are always laminated. Fig. 165 has been drawn to suggest this, the core being built up of sheet iron cut to required form and piled up with the sheets lightly insulated from each other. This is necessary for the same reason that a dynamo armature core is laminated; the reversing flux produces both a hysteresis loss and an eddy-current loss. The amount of these losses is greater in transformers than in armatures since the rate of reversal of flux is so much higher. Hysteresis loss is kept small by the choice of desirable kinds of iron; eddy-current loss by making the laminations thin (often no more than 0.007 in. thick). The laminations are bound tightly together so they cannot rattle against one another and produce a noise when the transformer is operating; they are placed so the flux has as nearly as possible a continuous iron path, without air gaps in which to flow, and are made so that usually the total cross-section through which the flux passes is the same at every point.

126. Classification by Methods of Cooling.—When transformers are in service, as the result of current flowing in the resistance of the windings, and also because of the eddy-current and hysteresis losses in the iron core, heat is generated. In order to keep the rise in temperature within reasonable limits some method of cooling must be used. Those regularly employed are mentioned below.

(*a*) *Natural Radiation.*—This is used with nearly all small transformers and with many large ones (see Fig. 167). The natural radiation from the surface of coils and core through the closed iron case, keeps their temperature from rising too high. It is usual, however, to immerse such transformers in mineral oil, which must be absolutely free from acid and moisture. In such case the heat generated in the transformer warms the oil and this by circulation carries heat to the case, by which it is radiated. Transformers are immersed in oil mainly to improve the insulation and to protect insulating fabrics from oxidation; but when covered with oil they are less accessible for transfer or repairs. In outdoor work a transformer planned for natural radiation if filled with oil will carry a heavier load with the same temperature rise, as illustrated by the following table:

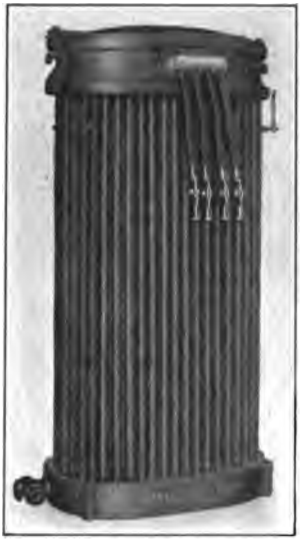


Fig. 167.

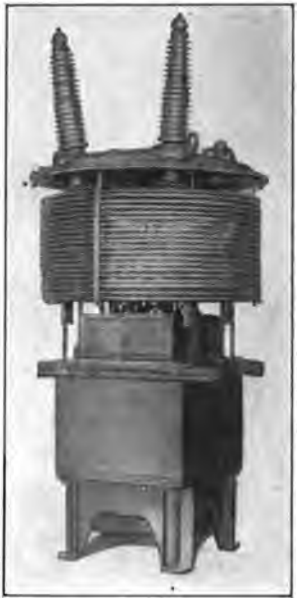


Fig. 168.

Watts capacity without oil	Watts capacity with oil
2,500	3,000
7,500	8,750
13,500	15,000

(*b*) *Oil-insulated and Water-cooled.*—On many large transformers in central station work not only is the transformer immersed in oil,

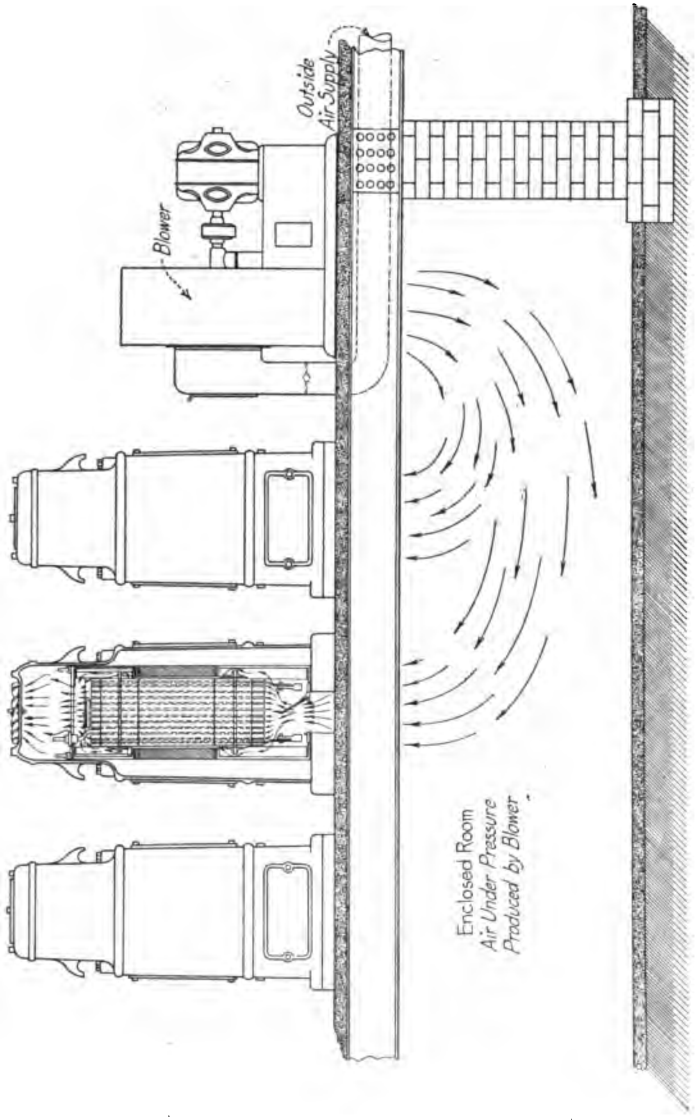

Outside Air Supply
Blower
Enclosed Room Air Under Pressure Produced by Blower

FIG. 169.

but a coil of pipe is also put inside the case through which water may be circulated and thus the oil kept cool. It in turn keeps the temperature of the transformer from rising too high (see Fig. 168).

(*c*) *Air Blast.*—The transformer is placed in a case arranged so that air entering at the bottom passes up over the transformer coils and core, eventually passing out at the top. Such a plan of cooling is only feasible in central and sub-station practice. A blower, usually motor-driven, forces the air over the transformer, which usually has its coils and core so subdivided that the air can easily reach large surface areas. A common arrangement is to place a row of transformers over openings in a box or chamber in which air is maintained under pressure by a fan. A damper under each transformer case turns the blast on or shuts it off. Through openings in the top of the case the air passes out. A pinwheel is often placed there to show by a glance when the blast is on (see Fig. 169).

127. Transformer Insulation.—In a transformer, insulated wire must of course be used so that the current flows through all the turns; but since the voltage on one coil is high, the primary and secondary coils are very carefully insulated from each other. An example of the importance of this may be seen by considering the practical case for which Fig. 170 furnishes the diagram. A supply of electrical energy at 2200 volts is delivered over the line *L* to a transformer which delivers 110 volts to lights on the secondary circuits. Suppose the secondary becomes crossed with the primary at *a* and on the supply line by chafing against the limb of a tree, a ground occurs at *E*. If now any person, while touching a water pipe or any other conducting or partly conducting thing connected with the ground were to touch the secondary circuit, at *b* for example, he would receive a 2200-volt shock.

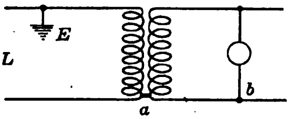


FIG. 170.

When high voltage is in use, insulation is as likely to fail by breakdown as by leaks. By an insulation breakdown is meant a failure similar in character to that which would have occurred if a mechanical force had actually broken it. A high voltage test of 10,000 volts is commonly applied between the two coils and also between the high voltage winding and the core, if the transformer is to be used with 1000 volts on its high voltage winding.

The importance of this barrier will also be clear if we remember that transformers are subject to age deterioration, to burn outs, and to damage from lightning.

128. Primary No-load Current.—If one of the windings of a transformer is selected and an e.m.f. applied to it, a current flows. Designs are always made in such a way that the amount of current which flows is determined by the reactance of the coil and not by its resistance. The presence of the secondary coil has no influence on the current flowing in the primary, for it is on open circuit. The current in the primary under these conditions lags far behind the applied e.m.f. Fig. 171 shows the relations, *OE* being the applied e.m.f. and *Ob* the current flowing. This current may be resolved into two components; a wattless current *Oc* and a working current *Oa*. The wattless current is what magnetizes the flux path. This may be clear if we remember that on any magnet (think of direct current) no power is required to maintain the magnetic flux. The same number of watts are spent in the winding no matter whether wound on the iron core of a good flux path or stretched out in a "straight away run" and not used to magnetize at all. The working current multiplied by the applied e.m.f. gives the watts spent. Since the coil had resistance so low that it will not overheat under full-load conditions these watts are practically all spent in core losses; that is in hysteresis and eddy-current losses.

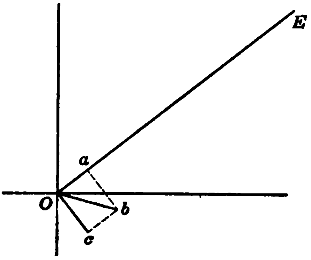


Fig. 171.

129. Ratio of Transformation.—In nearly all transformers, as already noted, the design is such that all the flux which passes through one coil must pass through the other. When the primary is connected to an A.C. circuit the flux through the magnetic circuit varies, and as it varies it sets up an e.m.f. which will be found in each turn of both primary and secondary windings. This e.m.f. multiplied by the turns in the primary, is the e.m.f. of inductance found there. The same e.m.f. per turn multiplied by the number of turns in the secondary is the number of volts generated in the secondary to be used in the circuit connected with it.

When the reactance is very large compared with the resistance of a coil the difference between the e.m.f. of inductance and the applied e.m.f. becomes negligible (see Fig. 154); and so they may be counted alike. This condition of affairs exists in the primary winding of a transformer. Hence we may write

$$\frac{\text{turns in secondary}}{\text{turns in primary}} = \frac{\text{e.m.f. induced in secondary}}{\text{e.m.f. induced in primary}} = \frac{\text{e.m.f. procured from secondary}}{\text{e.m.f. applied to primary}}.$$

The ratio of transformation in a transformer is that of the e.m.f. procured from the secondary to that applied to the primary. It is the same as the ratio of the turns in the coils and is practically constant for commercial transformers supplied from constant potential circuits no matter what the amount of current flowing in each of the coils.

It may be remarked incidentally that a transformer can operate only with alternating current. Varying flux due to the alternating primary current is the cause of the secondary e.m.f.

130. Operation Under Load.—Suppose that with the primary connected to a constant-potential circuit the secondary circuit is closed and it delivers current to a non-inductive circuit such as a load of incandescent lamps. If the ratio of transformation is constant, the magnetizing current must be constant, for it settles the amount of the varying flux and so of the e.m.f. generated per turn of secondary. The flux in the core varies between the same maximum amounts for all values of current passing through the circuits. The current flowing in the secondary will be in phase with the e.m.f. sending it. The secondary e.m.f. is in phase with the e.m.f. of inductance in the primary (generated by the same varying flux) which is in turn 180° in phase away from the applied e.m.f. See the right-hand diagram in Fig. 154 to confirm this.

Suppose 50 amp. at 100 volts is in the secondary circuit and that the ratio of transformation in the transformer is $\frac{1}{20}$. 2.5 amp. of working current at 2000 volts must then be flowing in the primary to account for the transformed power. The 2.5 amp. are in opposite phase to the 50 amp. and so the ampere-turns of the primary exactly neutralize those of the secondary, leaving the magnetizing current to maintain the same varying flux as though there were no load. In the primary circuit, under the conditions above stated there will be a current flowing as marked in Fig. 172. *Oa* is the magnetizing part, *aA* the working part for supplying secondary energy. The real current flowing is *Ob* which may be thought of as having the three parts mentioned. *Oc* and *Oa* are drawn to the same scale as in Fig. 171. *OE* the applied e.m.f. is not drawn to scale. Note how the power factor of the circuit has improved as the secondary is loaded. When the secondary is on open circuit the primary power factor may be as low as 0.5, while on full load it may be more than 0.9.

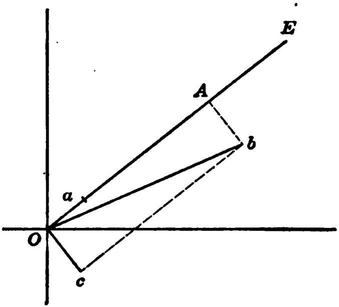


Fig. 172.

131. Regulation and Efficiency.—Even when the primary is supplied with exactly constant potential a practical transformer has less volts at the secondary terminals under load than when the secondary is on open circuit. This is due in part to the small resistance in each of the windings; in part to magnetic leakage. However small the resistance of the coils it cannot be made quite negligible; no matter how careful the design some flux will pass through the primary under load, which will not get through the secondary. By the regulation of a transformer is meant the ratio of the rise of secondary terminal voltage from full load to no load, to the secondary terminal voltage, expressed in per cent., constant potential being supplied to the primary. Thus a regulation of 2 per cent. on a 100-volt secondary means that with 100 volts at full load, 102 are delivered at no load. In a table below the regulation for some sizes of modern transformers is given. Should the load on the secondary be inductive the regulation is much poorer than that stated below.

The losses in a transformer are small and the efficiency therefore high. The losses are all in heat, part in the windings and part in the core. Those in the core are called core losses; those due to I^2R in the windings are called copper losses. In the design particular care is taken to keep the core loss small because when working with open secondary only a few watts need be supplied. The following table gives amount of core loss (constant for all loads), of copper loss for full load (both primary and secondary) and the full-load efficiency, of a high-grade modern transformer.

Kw. capacity	Core-loss watts	Copper-loss watts	Regulation, per cent.	Efficiency, per cent. (full load)
0.6	16	15	2.6	95.0
1	20	24	2.5	95.8
2	29	43	2.3	96.5
4	40	75	1.95	97.1
10	79	150	1.65	97.8
20	129	272	1.5	98.0
30	165	270	1.3	98.2
50	242	546	1.2	98.4

The core loss in a transformer is continuous while it is connected to the supply line. The copper loss is only present when current is taken from the secondary, and varies with the load. The "all-day efficiency" of a transformer is therefore of much practical importance. It is determined by dividing the watt-hours supplied by the transformer in 24 hr. by the watt-hours delivered to it from the primary line in the same time. It is usually computed on the basis of 5 hr. of full load and 19 hr. of no load.

132. Distributing Current by Transformers.—A very large number of transformers are connected in distributing circuits as shown in Fig. 173. The primary line goes down the street supported on insulators on the top crossarm. This is tapped and through primary fuses (shown on second crossarm), current goes to the transformer primary. Leads from the secondary go to a customer's line (the service connection) by a direct line, from insulators on the lower crossarm. Oftentimes the secondary line is carried along the same route as the primary but on a lower cross-arm. The secondary line is tapped at any point where a customer requires current. This arrangement is often extended so that a secondary network is formed similar to that described in section 77 for direct current, a transformer secondary being connected like the feeder connection shown there. Such an arrangement is used so that a small number of transformers of large size may serve a large number of customers. This improves the all-day efficiency and reduces the cost of transformers required.

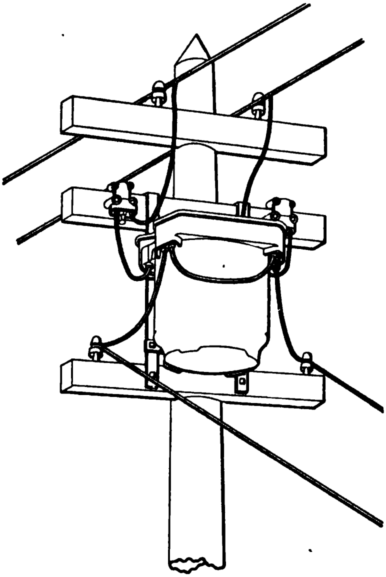


Fig. 173.

Transformers arranged for lowering voltage to customers are frequently made with two primary and two secondary windings. In Fig. 174 the transformer of Fig. 173 is shown in a plan view with the cover removed. The two primary windings (*aa'* for one, *bb'* for the other) end in terminals on a porcelain terminal block under screws on brass plates. These windings are put in parallel in Fig. 174 by means of strap connections shown. In Fig. 175

the windings are put in series. If they are right for a 1100-volt primary line in Fig. 174 they will be right for a 2200-volt primary line when connected as in Fig. 175, for with a given self-induced e.m.f. per turn, 1100 volts will be induced in each primary winding in either case. Hence the flux through the core will be normal in each case. It must be noted in this connection that the windings must have the proper ends connected when such arrangements are made. Consider Fig. 175. If *a′* had been joined to *b′* and *b* connected to the other side of the primary line, the primary fuses would at once have blown, for the flow of current could produce no flux through the core and so no counter e.m.f. Every transformer maker "poles" the windings so that if his standard method of connections is followed, a proper connection of the windings is always secured.

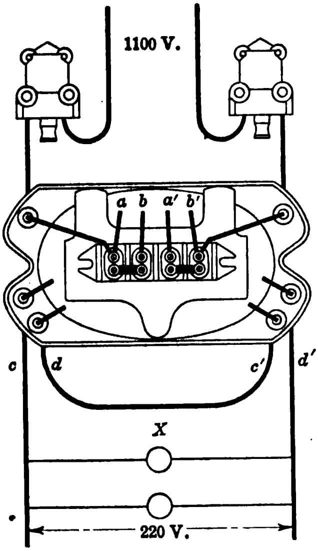


Fig. 174.

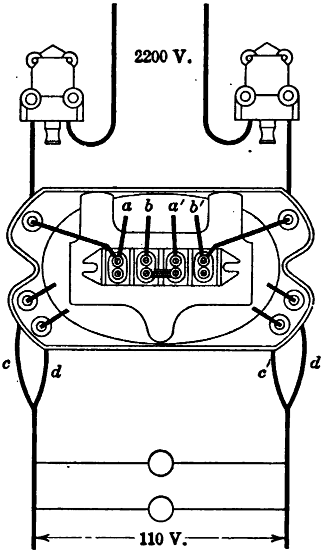


Fig. 175.

In a similar way the two secondary windings are connected in either series or parallel. In Fig. 174 the two windings are *cc′*

and *dd'*. The ends are brought out through porcelain bushings and the cross-connections made outside the transformer. Secondary fuses are reached at the entrance to a customer's premises. It is very important to have these windings properly "poled." If *c'* were joined to *d'* and *d* connected to the other side of the secondary line, Fig. 174, no voltage would be available. If in Fig. 175 *c* were joined to *d'* and *c'* to *d* the secondary windings would be in parallel, but if the primary were connected to line the secondary windings would be burned out if the primary fuses failed to open the circuit. The reader will do well to study this out carefully and also go over the marked secondary voltages in Figs. 174 and 175 to be sure he sees they are correct; the same transformer is simply reconnected in the second figure.

133. Three-wire Distribution.—On alternating-current, low-voltage secondary distributions the three-wire system is used as much as on similar direct-current work. Secondary networks are commonly three-wire systems, and individual customer's connections, except those having a very small number of lights, would be made the same way. Referring to Fig. 174, if a wire were connected at *X*, it would become a neutral and 110-volt apparatus would be connected between it and either of the distribution lines shown. Transformers are made expressly for use on three-wire distributions. If of the core type they would have the secondary winding so arranged that half of that for each side of the system is on each leg of the transformer. The voltage of each side on unbalanced load is better maintained when this is done.

Very frequently the neutral of a three-wire system is permanently grounded. This is done as security against danger to customers as the result of a cross with the primary. Even if a ground on the primary line coupled with a cross between primary and secondary exists, a person coming into contact with either side of the secondary circuit could not receive a shock due to more than the voltage carried between that side and the ground.

134. High-voltage Transmission.—Transformers are often used at both ends of a transmission line: at the sending end to raise the voltage for transmission; and at the receiving end to lower it for use. Such transformers differ from others already described only in the careful arrangement of parts to secure necessary insulation. The voltage in modern practice may be raised to as much as 150,000 volts. Fig. 176 shows a possible arrangement for such

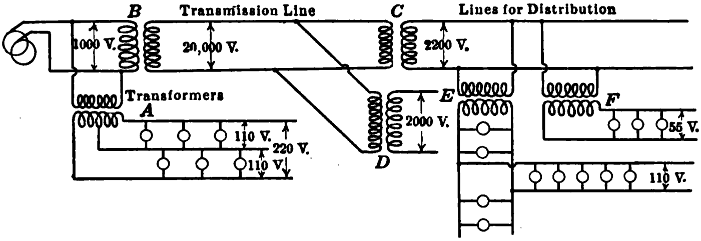


Fig. 176.

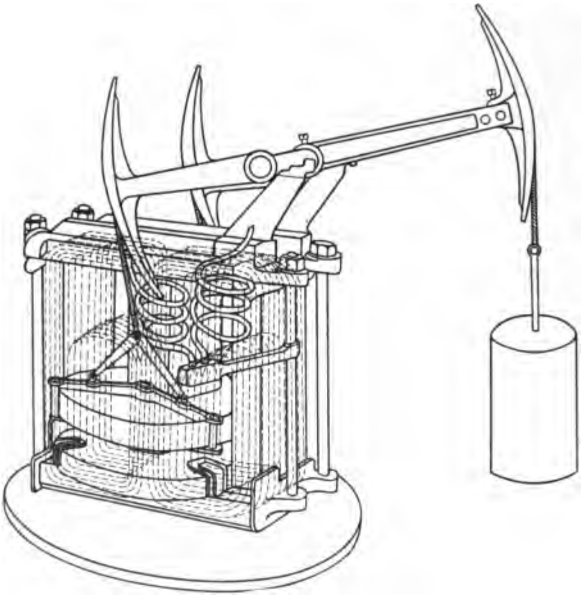


Fig. 177.

transmission. No particular relation exists between the size of the raising transformer *B* and those for lowering the voltage again.

135. Constant-current Transformers.—A good many circuits for lighting street lamps are arranged with the lamps in series. A constant current must be supplied over them if the lamps are to give a constant light. Alternating-current dynamos operate at constant potential. A certain sort of transformer affords the means of transforming the constant volts and variable current to constant current and variable volts. Fig. 177 shows an arrangement of such a transformer. It has the shell type with a fixed primary and a secondary hung from a lever weighted at the other end. This weight nearly balances the weight of the secondary coil. If the secondary circuit is open the secondary coil rests on the primary. If the secondary circuit is closed a magnetic repulsion between primary and secondary coils drives the secondary upward. This repulsion is easily understood by applying some simple principles stated earlier. The currents in primary and

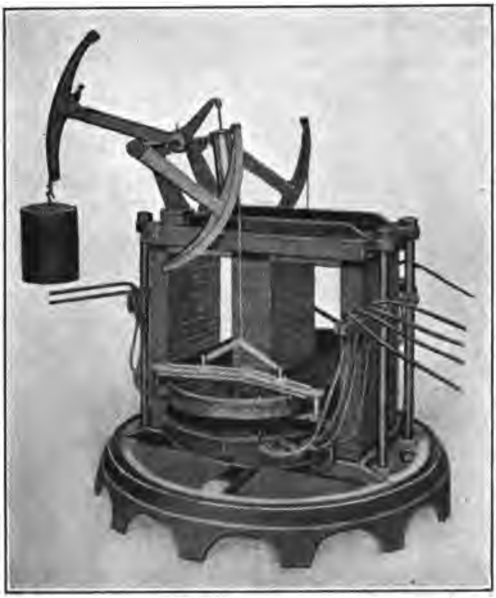


Fig. 177*A*.

secondary are in opposite phase, that is in opposite direction. Consider a wire of the secondary carrying current and placed in the magnetic field of the primary. Fig. 178 shows such an arrangement. Apply the rule of section 84 and the direction the secondary moves is upward. By suitable balancing weights a very slight upward thrust of the current in the secondary will drive it away from the primary. As it moves away, the volts generated in it diminish because a considerable part of the flux through the primary does not follow the iron magnetic circuit but crosses the air gap between the primary and secondary coils. A decrease in the resistance of the secondary circuit results in an increase of current, hence in a greater repulsive effect. The secondary coil moves farther away and as the voltage diminishes due to the new position, the current is reduced to nearly its former amount. By suitably arranging the balancing the current will stay practically constant for all resistances of the secondary circuit up to the maximum for which it was designed.

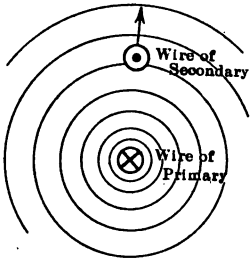


Fig. 178.

The primary applied e.m.f. may be any desired value. The current produced in the secondary is commonly one of the following values: 3.5, 4, 5.5, 6.6, or 7.5 amp. The power factor of the primary is not over 0.8 at best. As the secondary recedes it rapidly becomes lower. In the usage of some makers the primary is fixed and the secondary moves, while in other cases the secondary is fixed and the primary moves.

136. Special Transformers.—*Auto-transformers* are those in which the same coil is used for both primary and secondary windings. Since in the primary a certain number of volts are generated per turn of winding, exactly the same as in the secondary, a tap may be made into the primary and part of it be used as a secondary. Fig. 179 shows the arrangement. If there are 200 turns in the primary and 440 volts are applied, a tap to the secondary so that 50 turns are included between its leads would mean 110 volts available. The figure is marked for a certain flow of current to suit the voltages stated. The current in primary and secondary circuits is opposite in phase. The ratio of transformation in auto-transformers is small, frequently ½ or 2. They are used to save expense where no danger will be incurred due to high voltage being connected with the secondary circuit.

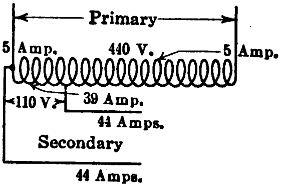


Fig. 179.

Feeder regulators are transformers having connections arranged as shown in Fig. 180. The primary is connected across the line and the secondary in series with it. By having a switch to select the number of turns of secondary which shall be used, the number of volts supplied to the feeder can be increased above those the dynamo supplied by a moderate amount or by reversing the secondary connection, reduced below what the dynamo supplies The switch has to be so arranged that the circuit can be kept closed all the time, but no secondary turns short-circuited when the switch is moved.

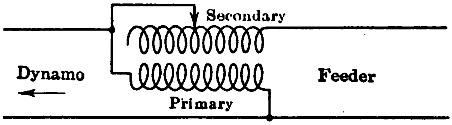


Fig. 180.

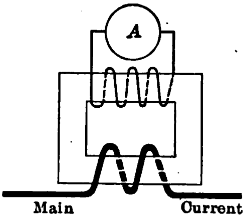


Fig. 181.

Series transformers are placed in series in a circuit to transform the current from one value to another. A very common use is in connection with switchboard instruments and control devices. It is desired to keep the high-voltage current from the indicating instruments and at the same time to change the current to an amount convenient to handle. The current in a main high-voltage circuit may be 50 amp. On a secondary circuit an ammeter is connected and through it a current of 5 amp. flows. Its scale is marked off to read 50, but only light wires entirely insulated from the main current are carried to it. The transformer design is made expressly to keep the ratio between the two currents fixed in amount. If the circuit to the ammeter should open for any reason a considerable impedance is introduced into the main circuit; a good many volts are therefore lost in the instrument transformer, and a voltage may be generated between the open ends of the instrument circuit large enough to be dangerous.

QUESTIONS AND PROBLEMS

1. A transformer has 1860 turns in one winding (*a*) and 93 in another (*b*). How many volts will be found between the terminals of *b* when 1000 volts are applied to *a*? How many from *a* when 100 are applied to *b*?

2. A transformer has a winding of 1160 turns for a primary, and it is intended to have 1040 volts applied. I want 208 volts on the secondary circuit. How many turns should be put in the winding? Suppose the primary applied voltage were raised 10 per cent., how many per cent. and to what voltage would the secondary e.m.f. be changed?

3. A certain transformer has 2200 volts applied to one winding (P) and at this time 355 volts are delivered by the other winding (S). (*a*) If the number of turns of winding in the S coil are 250, how many in the P coil? (*b*) If 20 amp. flow in S coil and are in phase with the volts there, how many amperes should be expected in coil P?

4. Why is it that the current in the primary coil of a transformer lags far behind the applied e.m.f. when the secondary circuit is open? Why is the power factor of the primary small when the secondary is lightly loaded, and large when the secondary is heavily loaded.

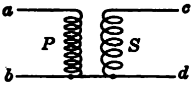
5. A 10-kw. transformer transforms from 2000 volts primary to 200 volts secondary. The primary resistance is 5 ohms and that of the secondary 0.05 ohm. The core loss is 150 watts. Calculate the efficiency at full load. (Count the load non-inductive and add the I^2R loss in both windings to the core loss for the total loss.)

6. A certain 10-kw. transformer has a core loss of 250 watts and a full-load copper loss of 100 watts. Calculate the all-day efficiency on the basis of 5 hr. of full load and 19 hr. of no load. (Add copper and core loss to output for input, and neglect copper loss at no load. Calculate everything in watt-hours for a whole day of 24 hr. The efficiency is the total watt-hours delivered over the secondary, divided by the total watt-hours supplied to the primary, multiplied by a hundred.)

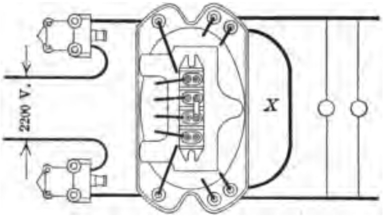
7. Recalculate the all-day efficiency for the transformer of problem 6 assuming the copper loss and core loss are exchanged. Compare with the result of problem 6, and state which transformer would be best to use in regular service.

8. Referring to the table in section 131 for data, determine by calculation whether it would be more economical in watt-hours used to supply current to a certain group of five customers by giving each one a separate 2-kw. transformer, or to group all of them on one 10-kw. transformer. Make the assumption that on the average the transformers work at half load. Assume losses in distributing lines may be neglected.

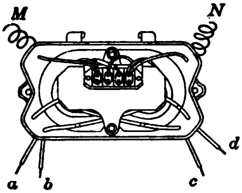
9. Referring to the middle of section 130 and to the figure here, tell how many volts there are from *a* to *c* and why. To the terminals *a* to *b* there are 1000 volts applied. The ratio of transformation is 1/10.



10. The figure here shown is for the same transformer as shown in Figs. 174 and 175. When 2200 volts are applied to the primary as shown, how many volts are delivered by the secondary circuit to the lamps and why?



11. In the figure we see a transformer in which when 2200 volts are applied between *M* and *N*, 110 are found on a secondary winding from *a* to *b* and 110 on another from *c* to *d*. How shall a determination be made of a plan of connections so the two secondary windings may operate in parallel? Make the answer practical and use nothing more than an incandescent lamp for testing apparatus.



12. A certain auto-transformer has its primary connections across a 2200-volt circuit. There are 1200 turns in this winding. At what points shall it be tapped to get 275 volts? At what points for 55 volts?

CHAPTER XII

POLYPHASE-CURRENT PRINCIPLES

137. First Definitions.—The term polyphase currents is used in connection with A.C. systems of distribution in which more than one current is used in the same distributing system. Each current flows in its own circuit but has the same frequency as others and is maintained at a fixed phase difference with them. So far single-phase A.C. only has been discussed, that is one which flows in a simple two- or three-wire circuit. The applications for polyphase circuits are shown in later chapters.

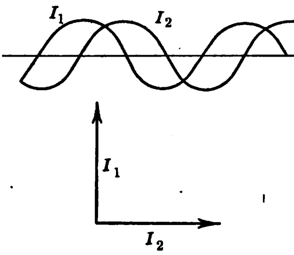


Fig. 182.

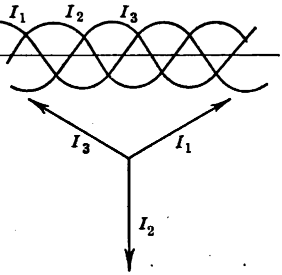


Fig. 183.

Two-phase currents differ in phase by 90° or quarter period. They are in quadrature, as shown in Fig. 182, where I_2 lags quarter period behind I_1. Three-phase currents differ in phase by 120° or ⅓ period. Each of the three lags ⅓ period behind the one next preceding. Thus in Fig. 183 I_2 lags 120° behind I_1, I_3 120° behind I_2, and I_1 lags 120° behind I_3. Two-phase currents and three-phase currents thus described are the ones in common use.

In order to generate the e.m.f. to send two-phase currents, we need only produce two alternating e.m.fs., one of which has a maximum value when the other is zero. The methods used for this as well as for generating e.m.fs. to send three-phase currents will be described in the next chapter.

138. Two-phase Circuits.—Think of two A.C. dynamos each of which generates an e.m.f. and sends a current through a circuit exactly as set forth in Chap. X. In addition suppose these e.m.fs. are somehow arranged to keep a fixed difference in phase-quarter period in this case. They are shown in Fig. 184. In a system such as this the apparatus supplied with current from one of the dynamos is said to be on the "A phase" and that supplied from the other to be on the "B phase." Between *a* and *b* any apparatus may be connected and the current which flows will obey the laws already stated. The same would of course be true of apparatus connected between lines *c* and *d*. If any practical electrician were engaged in running these four lines by the same route, he would be certain to think of combining two of them into a common return. This is done in Fig. 185, lines *b* and *c* having been combined. The connections now suggest the common three-wire system, but conditions are quite different. The 100 volts delivered by No. 1 machine combined in series with 100 volts from No. 2, taking account of the phase difference, will give the volts from *A* to *C*. They are combined in Fig. 186, the value marked being obtained from $\sqrt{100^2 + 100^2}$. The diagonal of a square is always 1.41 times the length of either side, and so to find the volts between the outer wires of a three-wire, two-phase system multiply the volts of either side by this number.

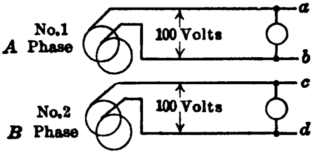


FIG. 184.

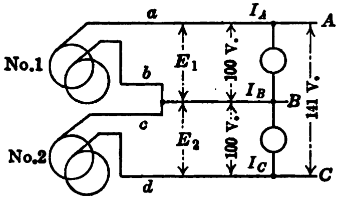


FIG. 185.

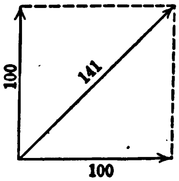


FIG. 186.

The currents flowing in the lamps are the same as those which would have been flowing if the system had been left four-wire as in Fig. 184. Suppose the lamps in Fig. 185 are alike and each has an impedance of 50 ohms. Currents I_A and I_C will then each be 2 amp. The current in I_B must be the combined value of I_A and I_C. Fig. 187 shows how this combined amount is $1.41 \times 2 = 2.82$ amp. But the common return might have been chosen by combining wires as in Fig. 189, where *b* and *d* make a common return and not *b* and *c*. Fig. 188 shows how the currents would then be combined. Notice that I_C is simply reversed and that the amount of I_B is the same as before. In passing it may be noted that when the four wires of a two-phase system are to be combined to make a three-wire line, either wire of the *A* phase may be combined with either one of the wires of the *B* phase to form the "common return," and exactly the same results be secured. Should the currents in the phase wires be different in amount, that in the common return is still easy to determine by the use of a figure like 187 in which I_A and I_C are given lengths representing their correct values. Measurements of I_B can be made when its calculation is too difficult.

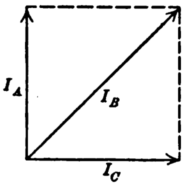


Fig. 187.

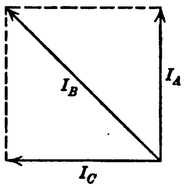


Fig. 188.

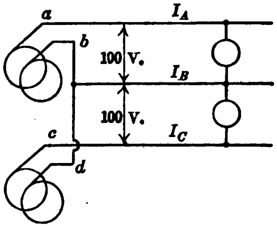


Fig. 189.

On a three-wire, two-phase line the outside wires only may be used and a *single-phase* alternating current be derived. Referring to Fig. 185, the 141 volts between *A* and *C* can be used for any purpose, but its value is usually sufficiently different from anything used on ordinary apparatus so that it is unavailable. To take current there would also cause the generators to operate with a bad power factor.

139. Two-phase Transformer Connections.—All the facts about transformers and transformer connections apply when used in polyphase circuits. There are polyphase transformers, but they are rarely used. Transformers as already described for single-phase circuits are connected in combination for polyphase work. In Figs. 190 and 191 are shown connections to two-phase high-voltage lines for transformers having a transforming ratio of $\frac{1}{10}$. In either case the secondary circuits may be handled four-wire or three-wire as desired. The results would be exactly as shown in Figs. 185 to 189, the line wires being similarly marked. In many cases in practical distributions, transformer No. 1 might be at one place along a line serving a customer and No. 2 at a different one serving a different one. The secondary of each transformer might have connections like those shown in Fig. 174 and a wire be brought out at *X* so a three-wire, single-phase system was secured (section 133).

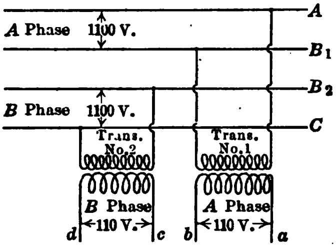


FIG. 190.

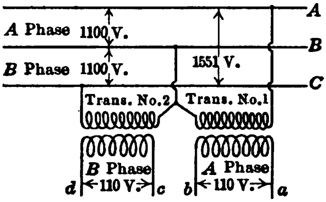


FIG. 191.

140. Three-phase Preliminary Notes.—Certain simple D.C. relations are presented here as an aid to making clear the e.m.f. and current combinations which are commonly found in three-phase circuits.

Fig. 192 shows two D.C. dynamos, each independently connected to its own load. The wires are numbered for convenience. Suppose each lamp takes 2 amp. from the line to which it is connected; then each of the wires 1, 2, 3, 4 has 2 amp. in it.

Refer next to Fig. 193. The same dynamo circuits are in use except for the fact that wires 2 and 3 have been combined for a "common return." The two dynamos are combined in series and the difference of potential from 1 to 4 is 200 volts while the current in the common return is zero. Note that by this combination of e.m.fs. in series a large e.m.f. results (in this case twice that of either one) and only a small current flows in the common return (in this case none at all).

But refer further to Fig. 194. The two dynamo e.m.fs. are still connected in series. We now have wires 2 and 4 combined for the common return. In this case the difference of potential from 1 to 3, the outside wires, is nothing, while the current in the common return is 4 amp. Note that now the e.m.fs. combined in series give a small result (in this case nothing) and that the current in the common return is big (in this case twice as much as in either one of the other wires).

There are only two ways to combine these e.m.fs. in series; one is as in Fig. 193 and the other as in Fig. 194. Any two e.m.fs. may be combined in series and results similar to those here noted be found. These principles from D.C. work should be kept in mind as the next paragraphs are studied.

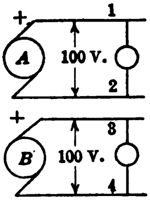


FIG. 192.

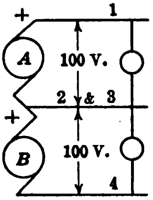


FIG. 193.

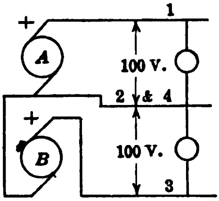


FIG. 194.

141. Four-wire Three-phase Connections.—It has been already stated (section 137) that three-phase currents are three separate currents having the same frequency but differing in phase by 120°, combined in a system. They must each be sent by its own e.m.f., and so three e.m.fs. with this same phase difference must be available. Sources for such e.m.fs. and line wires from them are shown in Fig. 195. Six wires for distribution are never used. In practice some combination is made use of to reduce the total number to 4 or even 3. In what follows the *A*, *B* or *C* phases will be freely referred to.

If E_A and E_B are connected in series, they must be joined either as shown in Fig. 196*a* or 196*b*. Figs. 197*a* and *b* show E_A and E_B, two e.m.fs. with 120° phase difference, combined by the usual methods of combining alternating e.m.fs. in series. If then the e.m.f. from 1 to 4 (Fig. 196*a*) is E_S, that from 1 to 3 (Fig. 196*b*) must be E_R, for the only difference is that the connections shown for E_B in Fig. 196*a* have been reversed for Fig. 196*b* as has also the line representing this e.m.f. in Fig. 197. The current in the "common return" in either case must be determined from similar diagrams, in which currents at 120° are combined. But if the two e.m.fs. are combined to make E_R, the current combination must be made as in Fig. 199 to get the amount in the common return (refer to the corresponding thing for D.C. in the previous section).

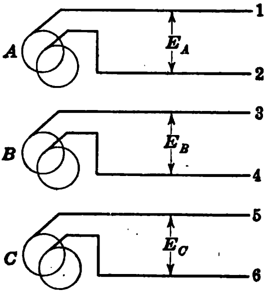


Fig. 195.

It must further be noted that since we are dealing with alternating e.m.f., the *diagram* of 196*a* need not necessarily be represented by 197*a*; it might be that the combination of e.m.f. in Fig. 196*a* is shown by 197*b*.

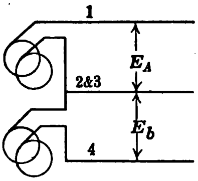


Fig. 196*a*.

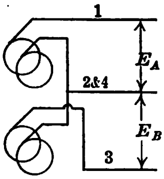


Fig. 196*b*.

Take Fig. 198 now in which a four-wire arrangement of a three-phase distribution system is shown. Wires 2 and 6 have been joined to 4 for a common return. If *A*, *B* and *C* each generate 100 volts E_A, E_B and E_C are each 100. From 1 to 3 the e.m.fs. of *A* and *B* are combined and care is taken to connect them to secure an e.m.f. as shown in Fig. 197*b*. The number of volts at P if carefully measured from such a figure, in which E_A and E_B were carefully laid off to be 100 units long, would be 173 volts. The diagonal of such a figure as that shown in Fig. 197*b* is always 1.73 times the length of either of the equal sides. Q and R are similarly made up of B and C and A and C respectively and each is 173 volts.

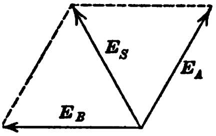


Fig. 197*a*.

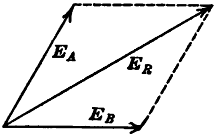


Fig. 197*b*.

Three lamps are shown connected. Each one receives current from its particular machine; *a* from *A*, *b* from *B*, *c* from *C*. The current in the common return 4 is now to be determined. That through lamps *a* and *b* together must combine according to the arrangement of Fig. 199, for e.m.fs. E_A and E_B were combined according to the arrangement of Fig. 197*b*. If I_A and I_B are equal, in this case laid off to be 2 amp. each, it will turn out

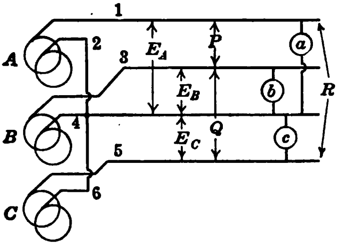


Fig. 198.

that I, their value when combined, is also 2 amp. Now the current which flows in the common return is the combination of I_A, I_B, and I_C. It has been shown that I_A and I_B together make I. Fig. 200 shows the three currents in their three-phase relation. A comparison of this figure with 199 will show that I is equal and opposite to I_C. Hence the current in the common return is zero (non-existent).

Note carefully that this is true only when I_A, I_B and I_C are all equal. In a considerable amount of three-phase work when the currents on phases *A*, *B*, *C* are apt to vary and be different, some current flows in the common return or neutral.

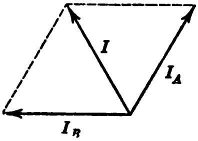


Fig. 199.

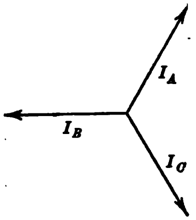


Fig. 200.

142. Three-phase Star Connections.—In cases where the load is "balanced," that is the currents on each phase are always the same, and there are a good many in practice, the common return can be omitted since no current then flows over it. The system takes the form of Fig. 201, the place for the neutral being from *a* to *b*. This style of connections is known as star or Y; the reason is suggested by the connections shown for the lamps in Fig. 201.

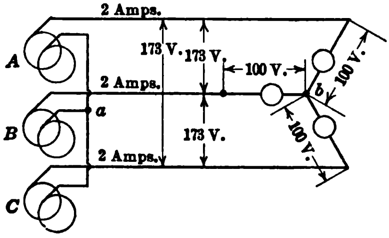


Fig. 201.

143. Three-phase Mesh Connections.—Another way of combining the three e.m.fs. is shown in Fig. 202. Wires 2 and 3 are joined for the common wire 7, 4 and 5 for 9, and 1 and 6 for 8. Dynamo *A* sends current to lamp *a*, *B* to lamp *b*, and *C* to lamp *c*. All three e.m.fs. being assumed at 100 volts, each lamp has that many volts to send current through it. Each machine sends current to its own consuming devices but the number of distributing wires has been reduced from six to three. The two e.m.fs. E_A and E_B between 1 and 4 are combined according to the plan shown in Fig. 197*a*. That is the volts from 1 to 4, E_A and E_B together, would be also 100. If the dynamos are successively passed through, 1, *A*, 2, 3, *B*, 4, 5, and *C* to 6 and on to 1 it will be noted that the machines are connected by a short-circuit through each other. If the connections are properly made, however, the combined e.m.f. of E_A and E_B turns out to be equal and opposite to E_C. Hence no current can flow by way of the short-circuit (see Fig. 203).

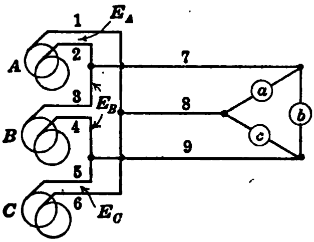


Fig. 202.

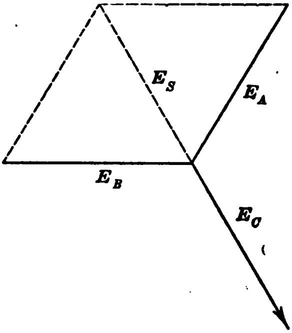


Fig. 203.

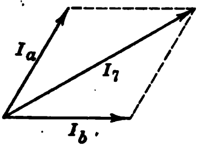


Fig. 204.

If the e.m.fs. have combined according to the diagram in Fig. 197*a* the currents must be combined in the common return wires according to the plan of Fig. 197*b* (see the corresponding thing for D.C. in section 140), The current in line 7 must be shown by the construction of Fig. 204. If I_A and I_B are each 2 amp., the current in 7 must be $1.73 \times 2 = 3.46$ amp. The same reasoning holds for each of the other wires 8 and 9. With this plan of connections the load may be balanced or unbalanced. Each dynamo supplies its own load.

The set of connections shown in this section are called mesh or Δ (that is delta, a Greek letter). The arrangement of the lamps in Fig. 202 will show the appropriateness of this designation.

144. Three-phase Transformer Connections.—Single-phase transformers are commonly used on three-phase lines. Any phase is transformed as though it alone were dealt with. Connections for lines where voltage is to be reduced for service connections to customers will be specially referred to. If single-phase A.C. only is required this is secured by connection to any one phase. Thus in Fig. 205 at *M* there is such a three-wire, single-phase connection and at *P* a similar one on another phase for two-wire connection. In distribution, care would be taken to keep the load nearly balanced among the phases when such connections are made. At *N* is a set of three transformers connected Δ to the primary 1100-volt, three-phase line, and also connected Δ on the secondary side. If the transformers have their primaries designed for 1100 volts and are arranged with a transforming ratio of $\frac{1}{10}$, 110 volts three-phase will be available on the secondary circuits. At *O* is shown a set of three transformers with primaries Y-connected to the same line. If the secondaries were also Y-connected, the transforming ratio being $\frac{1}{10}$, a three-phase secondary 110-volt line would be available. This connection is not often used, for transformers are built to receive standard line voltages like 1100, 2200, etc., while here each would have only 636 volts applied to it. When star connection is used the neutral point (marked *Z*) is often grounded; not so that a fourth wire of the system may be secured through which current may flow when there is an

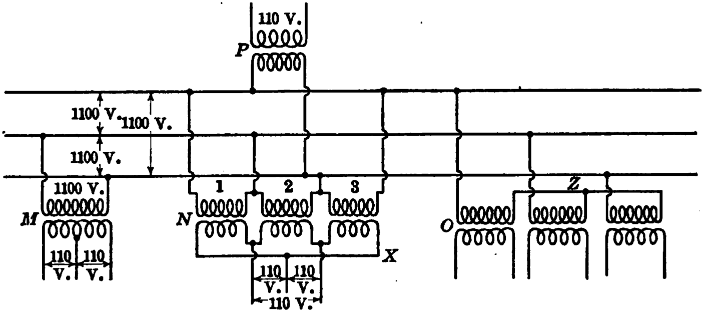


FIG. 205.

unbalanced load, but so that by means of a "ground" the same advantages may be secured as already referred to in section 133.

If primary connections are made Δ there is no reason why secondary connections should not be made Y and *vice versa*.

The convenience of using standard voltage alone, accounts for the common plan of using the same connections on each side.

In any case the connections among the secondary terminals have to be handled carefully and intelligently. With Δ connections it is easy to make a bad short-circuit. Before the connections at *X* were closed, for example, it must be known that there is no difference of potential there. If there is a difference of potential one of the secondaries must have its connections reversed.

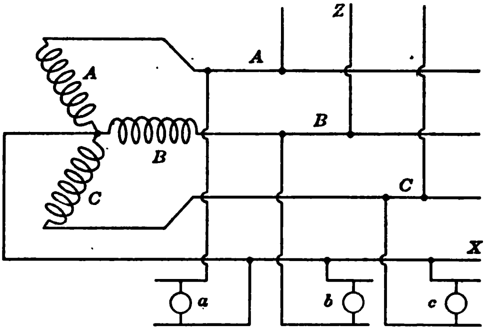


FIG. 206.

In a similar way for Y-connections such e.m.fs. as shown in Fig. 197*a* rather than those indicated by Fig. 197*b* may be secured by a reversed connection of secondary leads.

The advantage of Y-connection from consideration of the cost of wire, is so great that four-wire secondaries are frequently used in distributing current in buildings. The primaries are best Δ-connected and transformers of standard transforming ratio used. Fig. 206 shows the transformer secondaries only, connected star; and a four-wire line marked *A*, *B*, *C*, *X*. If the primary line is 2500 volts and the transforming ratio $1/20$ the lamps (shown connected) are supplied with 125 volts. It should be noted that lamps connected like *a* receive current only from one of the transformers; hence an unbalanced star-connected secondary load produces no difficulty like that when the neutral line *X* is not in use. It should further be noted that the three wires *A*, *B*, *C*, constitute a 216-volt three-phase distribution system. This might be used for operating special three-phase apparatus or any balanced load. The wires would be taken out as shown at *Z*.

145. V-connections, Three-phase.—One of the advantages of the Δ-transformer connection for three-wire, three-phase lines is found in the fact that if one of the transformers develops a defect and must be cut out the three-phase load can still be carried on the other two. In Fig. 207 suppose transformer *C* to be cut out. Lamp *c* will not go out for it is across the terminals of *A* and *B* in series. But the combined e.m.f. of *A* and *B* is the same as that developed in *C* (refer to E_3 in Fig. 203). The three lamps will all burn as before but an unbalanced load would thus be put on the system. A connection making use of the two transformers only on a three-phase system to supply a three-phase load is known as a V-connection. It is used sometimes to save transformers when only a small amount of power is to be used.

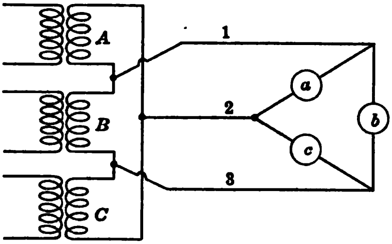
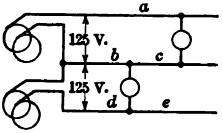
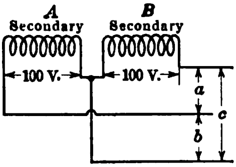


FIG. 207.

QUESTIONS AND PROBLEMS

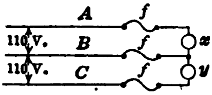
1. On a certain two-phase line there are two 750-watt incandescent lamps. Determine the amount of current at *a*, *b*, *c*, *d*, *e*. Determine also the amount at each place if the lower lamp is turned off.





2. On a two-phase line the wiring from transformer secondaries is done as shown here. Determine the volts at *a*, at *b*, at *c*.

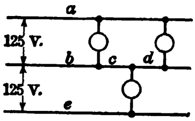
3. Here is a two-phase three-wire system. *fff* are fuses. Due to some peculiar effect the fuse in line *B* melts off. Lamps *x* and *y* are precisely alike (take them at 110 ohms). How many volts on each and what current through each (*a*) before the fuse opens; (*b*) after it opens.

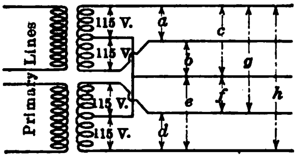


4. On a two-phase system with balanced load on a three-wire distribution 12 kw. is being distributed at 200 volts at a power factor of 0.8. Calculate the current flowing in each of the three lines.

5. Using Fig. 191 draw completed secondary circuits, putting on them a balanced load of 50 100-watt lamps, and calculate the current in each of the primary wires *A*, *B*, *C*.

6. For the two-phase line shown at the left below determine the amount of current at *a*, *b*, *c*, *d*, *e*, where each lamp has an impedance of 25 ohms. (Refer to the end of section 138, and measure diagram if calculation cannot be made.)



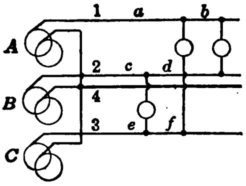


7. Above at the right is a diagram for current distribution on a two-phase system. Find and record difference of potential between lines as indicated at *a*, *b*, *c*, *d*, *e*, *f*, *g*, *h*. Show your work.

8. Referring to Fig. 201, determine the values of e.m.f. between various lines (like those in that figure) if each alternator has a terminal P.D. of 220 volts. If each is delivering 10 kw. at a power factor of 0.9, how many amperes are flowing on each of the three wires?

9. If in Fig. 202 wire 9 were to break, what changed conditions would be found? It is assumed that each dynamo delivers 120 volts, and each current-using device had 4 amp. through it before the wire broke. Make the answer numerical to show current in each device and over each line.

10. In the figure here shown the terminal voltage of each alternator is 100 volts. Each lamp receives 500 watts. What current is flowing at each lettered point? The usual three-phase dynamo relations and plan of connections hold.



11. In the figure made for the preceding problem determine the volts between each line wire and every other line wire.

12. I have to connect 45 incandescent lamps to a three-phase secondary system. No more than 9 can be connected to any branch two-wire line. Make a diagram to show how to connect them. Let the connections include the secondary coils of necessary transformers. Show a balanced load.

13. A three-phase three-wire system is so arranged that there is a P.D. between wires of 1000 volts and 34.6 amp. flows in each wire. There are three transformers connected Δ through which, on secondary circuits, the load is served. Calculate the current in each transformer primary, and the power supplied over the system to them at a power factor of 0.9. (For the last determine the power of one transformer and multiply by 3.)

14. The primaries of three transformers have been connected to a three-phase line as shown at *N* in Fig. 205. How would you proceed in the practical case to determine how to connect the secondaries in order to have the proper Δ connection? No testing apparatus except a 110-volt incandescent lamp is to be made use of.

15. There are three wires coming from a generating station. It is not possible to examine machinery in the station, but any tests desired may be made. How could one tell whether the system was (*a*) direct-current, three-wire; (*b*) alternating-current, three-wire, single-phase; (*c*) alternating-current, two-phase; (*d*) alternating-current, three-phase. Assume low voltage distribution.

CHAPTER XIII

ALTERNATORS

146. Generation of Alternating E.m.f.—Fig. 208 represents an outline carcase for a multipolar D.C. machine. A smooth drum armature core is arranged to revolve within a set of poles around which direct current flows magnetizing the flux paths in the usual way. A wire secured to the outside of the armature core would have e.m.f. generated in it when in position *a* on line 2; none when in position *c* on line 3, etc. In the lower part of the figure a plot is made to show how this e.m.f. would be. The e.m.f. is in one direction at *a* and is in the opposite direction but equal in amount when at *b*. The plot shows something which suggests an alternating e.m.f., two cycles being completed in one revolution of the conductor as it cuts the flux. As the conductor passes before a pole the rate of cutting flux is constant and so the generated e.m.f., as indicated by a horizontal line in the e.m.f. curve in the region 2, or 4 in the figure. If now a coil be made exactly like that for a D.C. drum armature with one side at *a* and the other

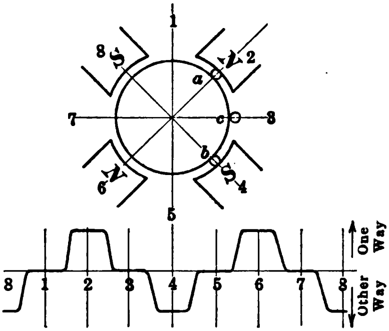


Fig. 208.

at *b*, the volts available would be the number generated in a wire multiplied by twice the number of turns in the coil, and the e.m.f. generated as the coil revolves would be alternating. A formula to use for any such armature winding, to express the amount of e.m.f. generated, might be arranged thus:

$$\text{Ave. } E \text{ (in volts)}^1 = \frac{2\Phi nc}{100{,}000{,}000}$$

The same symbols as those in section 39 are used, the average e.m.f. generated in any wire multiplied by the number of wires on the armature giving the total e.m.f., if all the armature wires are in a single series. Since, however, it is the *effective* e.m.f. we are interested in, and the relation between it and the amount above depends on various matters including the particular practical arrangement of the winding and the wave shape of generated e.m.f. (referred to in succeeding sections), the only way to arrange the formula is to state it with a letter *K* included, for which the proper number belonging to the armature considered may be substituted in making calculations:

$$\text{Effective } E = \frac{2K\Phi nc}{100{,}000{,}000}$$

147. Armature Winding for an Alternator.—Four coils may be placed in positions similar to the one on the core with one side at *a* and the other at *b*. They may be connected in series so that all the individual e.m.fs. will add. Fig. 209 shows the connections, the armature being in position for maximum e.m.f. Some means must be provided for continuously keeping hold of the ends *m* and *n* and then the alternating e.m.f. can be used to deliver current to a circuit. For this purpose insulated metal rings, called slip rings or collecting rings, are placed in a location similar to that used

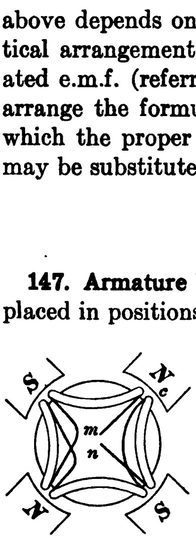


FIG. 209.

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[1] The student must not make the mistake of thinking that any alternating e.m.f. might have an average value of zero, because it is half the time in one direction and half the time a similar e.m.f. in the other direction. Since it sends a current it could not have an average value of zero. By average value is meant the average numerical value in any half cycle, or the average without regard to direction.

for the commutator of a D.C. dynamo. On these brushes rub and through them current is delivered to the external circuit (see Fig. 211).

Smooth core armatures are not in use. To make the design of Fig. 209 practical, a large and shaped tooth form may be used with a coil wound around each tooth. Each coil might contain 50 or more turns. Fig. 210 shows how this would be done. The coils are shown connected in series. To assist in making the winding plain, a perspective view of the arrangement of two coils is shown on the right, while below there is a reproduction from a photograph of such an armature in process of construction. It is only alternators of older types which have this style of tooth construction. If the machine had eight poles and eight coils were connected in series on the armature to generate 1000 volts, each one would generate 125 volts. If it is desired to change the same machine so it produces 250 volts, all that need be done is to separate the coils into four lots of two in series and join the four sets thus secured in parallel connection. Fig. 211 shows

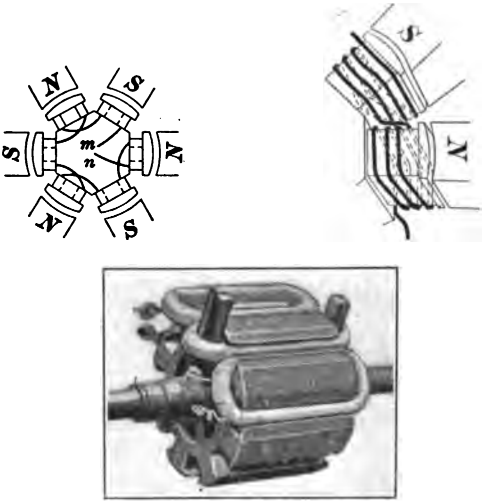


FIG. 210.

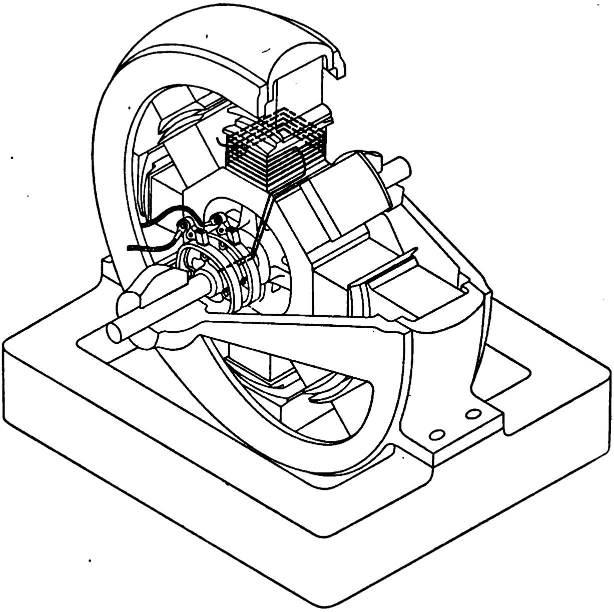


Fig. 211.

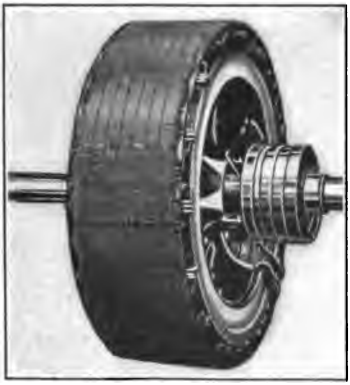


Fig. 212.

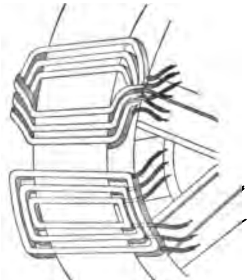


Fig. 213.

how the connections are brought out to collector rings and the e.m.f. made available in the external circuit.

Most machines have armature cores slotted like those for D.C. machines and form-wound coils are disposed in them. The arrangement in Fig. 212 is equivalent to subdividing each of the coils of the winding described in the last section into two or more parts, these subdivided coils being spread over enough surface so that each has a different slot from the others. Fig. 213 shows two ways in which this may be done, three coils taking the place of a single large one. After being placed, the ends would be so joined that the e.m.fs. of any set would add up in one series; the sets would then be connected in series or parallel as desired.

148. Frequency and Wave Shape.—In connection with Fig. 208 it has been noted that a cycle of generated e.m.f. has been passed when a particular point of the armature has passed two poles. Hence the frequency of an alternator is obtained by multiplying the number of pairs of poles (half the number of poles) by the revolutions per second of the armature. In order to secure commercial frequencies, machines must be quite multipolar unless the speed is very high. In case of alternators connected to high-speed turbines, two-pole or four-pole machines are common. When direct-connected to slow-speed engines the number of poles may be sixty or more.

The wave form is regulated by the way in which the winding is distributed and by the way the flux spreads over the pole face. By shaping the poles, altering shapes of teeth, or modifying distance from armature core to pole face at different places under the same pole the distribution of flux across the pole face can be regulated. Most machines are designed to produce wave forms such as are shown in the figures accompanying Chap. X rather than such as represented in Fig. 208.

149. Field Excitation.—In order to set up and maintain magnetic flux through the magnetic circuit of an alternator, direct current must be used. This current is derived from a separate D.C. machine. In many cases this machine, "the exciter," is belted from the alternator (see Fig. 214). In some cases a D.C. armature is mounted on the same shaft with the A.C. armature whose fields it supplies with current, while in large stations the

D.C. for excitation is supplied from an independent power plant. A 5000-kv.a. machine operating at high efficiency might use 100 kw. of direct current for field excitation.

Alternators are built to supply constant-potential circuits. As the current drawn from them grows, the volts supplied would drop like the upper part of the curve for the characteristic of a shunt dynamo (see *a* to *b*, Fig. 80). On short-circuit the current delivered by an alternator would be quite large, perhaps four or five times full-load current. It is not more because the reactance of the armature coils is more important than their resistance in controlling the current which flows. If the voltage is to be maintained constant at machine terminals, therefore, the field current must be increased as the load on the dynamo gets bigger. This is frequently done by hand adjustment of rheostats in the exciter circuits.

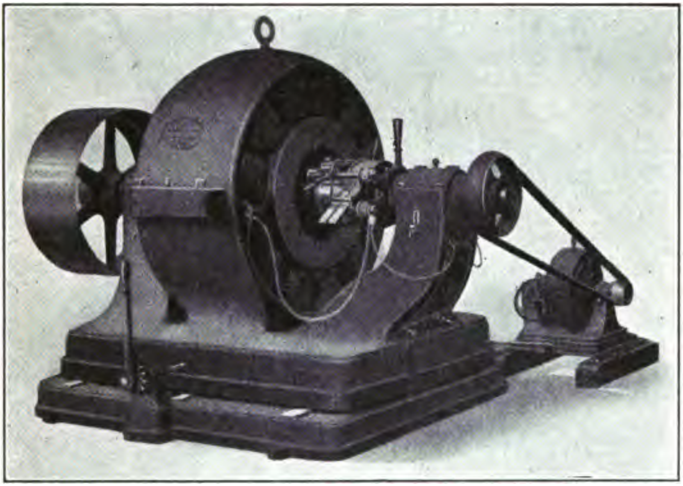


Fig. 214.

In the past, alternators were made with arrangements which included field windings like those for compound D.C. dynamos to secure constant potential. Few of them are now in use.

The field excitation necessary in order that a given voltage be supplied depends not only on the load on the machine but also on the power factor of the load. The left hand part of Fig. 215 shows an armature coil in the position it has when generating maximum e.m.f. This would also be the time of maximum current on a power factor of 1. If the power factor were 0, that is if the current lags quarter period, the right hand part of Fig. 215 shows the position the armature has reached when the same coil has maximum current in it. The direction of current in the armature winding and the direction of the field current magnetizing the south pole are both marked. Since they are oppositely directed, the armature current is demagnetizing and the field current would have to be increased enough to compensate. That is, the field ampere-turns must be increased by the number in the armature winding to maintain the same flux as before. If the power factor is larger this increase of field current need not be so much since the armature current when maximum is not in such a favorable demagnetizing position. On a low power factor the field excitation of an alternator may have to be made so great that the field windings overheat.

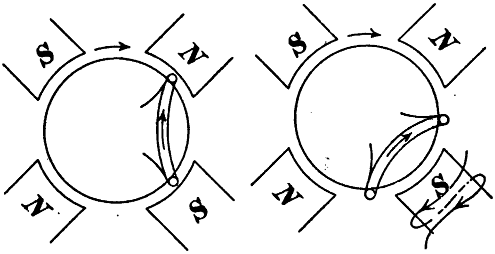


Fig. 215.

150. Stationary Armatures.—Since alternators have no commutators it is as easy to revolve the field structure and keep the armature stationary as it is to have the armature revolve in the same manner as it does in a D.C. machine.

The common plan is to have a revolving field inside a stationary armature. Fig. 216 shows the appearance of such a field for small alternators. The special forms used in very large machines will not be here described. Fig. 217 shows the armature and Fig. 218 shows the appearance of such a machine complete.

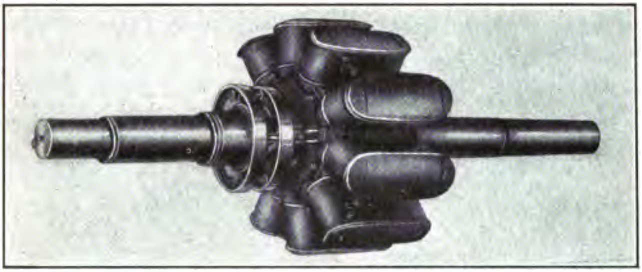


Fig. 216.

When the field revolves, collector rings are provided as the means whereby current may be taken into the field winding and brought out again. The armature winding ends in connecting plates on a terminal board; or, on a high-voltage machine, in wire terminals to which machine leads are directly connected, the connection being then covered with insulation. Revolving field machines

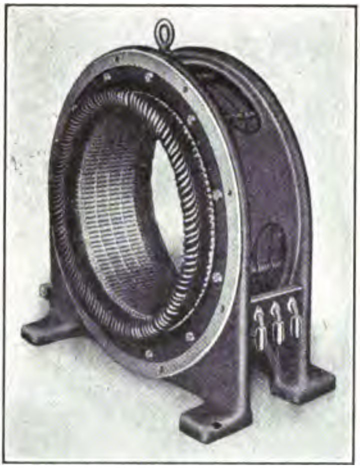


Fig. 217.

are much preferred for high voltage. The armature windings are much easier to insulate when they remain stationary; the high-voltage leads can be taken out at a place where they are quite inaccessible to the operator while the difference of potential at the collector rings is small.

Since modern alternators are almost invariably polyphase machines, the examples given have shown machines of that kind. The arrangement of their armature windings is shown in succeeding sections.

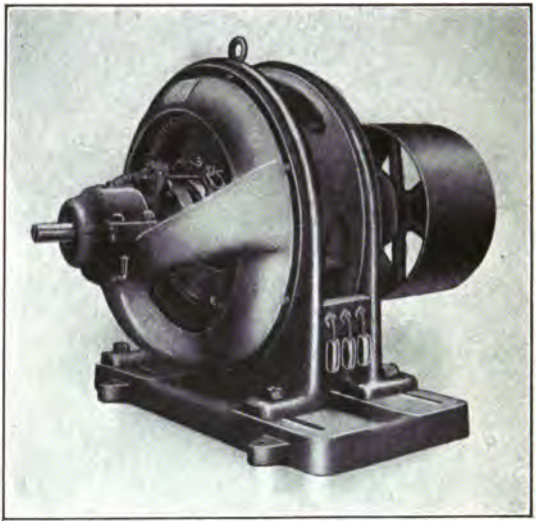


FIG. 218.

151. Two-phase Armature Winding.—In Fig. 219 a coil *xx* is shown on an eight-pole revolving armature alternator which is in position to generate maximum e.m.f. If the winding were not concentrated in a single coil but "distributed," its subdivisions might have been spread between *a* and *b* and also between *c* and *d*. None would have been found between *b* and *c* or between *d* and the near edge of the next *N* pole, because in those locations no e.m.f. would be generated. This then would be waste space on a single-phase armature winding. But it is just the right space to use for the winding of the other phase, for when in one phase maximum e.m.f. is generated, in the other there is no e.m.f. *yy* represents then the proper location for a coil of winding for the other phase.

If all the coils to complete the winding were shown in place there would have been a set like that shown in Fig. 219 for the *A* phase and another in intermediate positions for the *B* phase. There would then be four ends to the windings and four collector rings will be required unless, before the ends are brought to the rings, one terminal wire of the *A* phase is connected to one of the *B* phase. There will then be three wires to connect to three slip-rings and the distribution line must be three-wire like that shown in Fig. 185 where two separate single-phase sources of e.m.f. were assumed, the interconnections being made outside the machines.

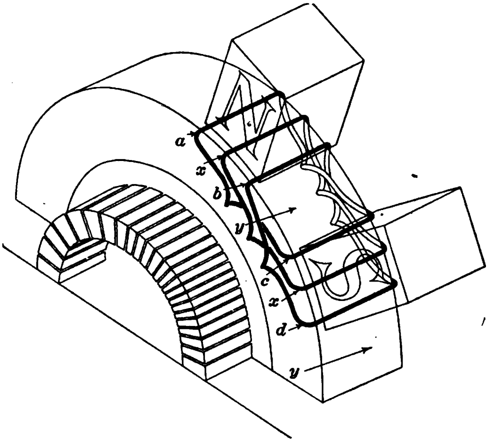


Fig. 219.

The same arrangement of coils in the two phases is shown for a revolving field machine having a large number of poles in Fig. 220. The winding is distributed, however, so that there are two slots per phase per pole. As shown the *A* coils are generating maximum e.m.f. and the *B* coils nothing. The *A* coils of the group shown are connected in series and one end (*n*) is carried toward the place where it would reach the next set of coils in the *A* phase. It is much more common to arrange such windings in two layers of coils. Such an arrangement is indicated in Fig. 221. A certain coil in the *A* phase goes from the bottom of slot 1 to the top of slot 5. Starting at *m* a wire in the first coil goes into slot 1, around on the back to 5, on to 1 again and so turn after turn until the coil is complete and its other end comes out to *q*. The next one, in series with it, goes from the bottom of slot 2 to the top of slot 6. These form a group and a connect-

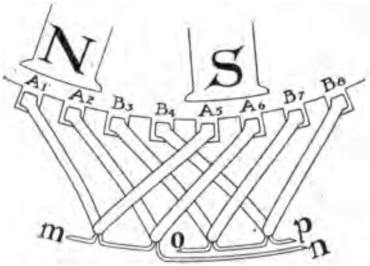


Fig. 220.

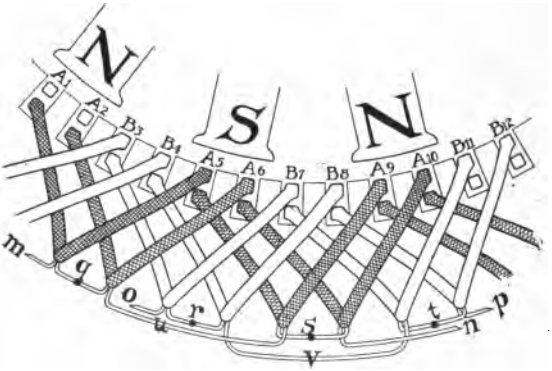


Fig. 221.

ing wire *u* runs on to a coil with one side in the bottom of slot 5, the other side being in the top of slot 9. The connection of the coils in series and the separate connections of the phases may be studied from the figure. In Fig. 222 is shown an actual armature winding of this kind, there being five slots per phase per pole. The wire ends of coils, ready for cross-connecting, show clearly. In a completed machine these cross connections are tucked back under the projecting ends of the coils and are covered so completely by the end shield, attached to the frame, that it is hard to trace or even to find them. In this figure the insulation in the slots around the formed coils, the ventilating ducts through the laminated armature core and the wooden wedging strips slipped into places made for them so the coils may

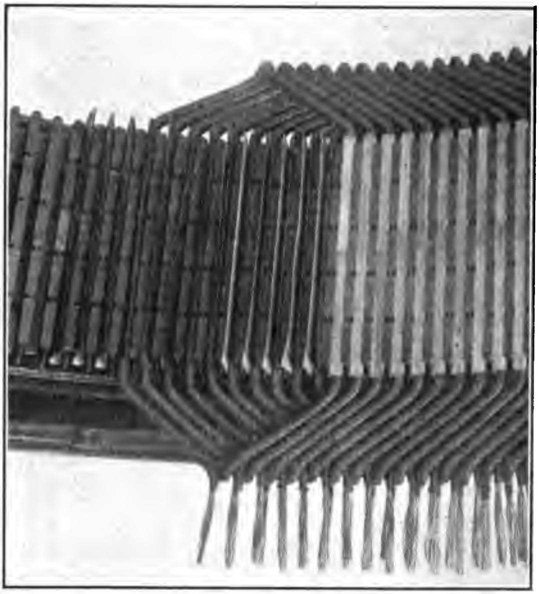


Fig. 222.

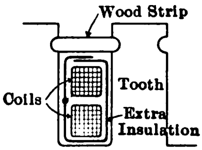


Fig. 223.

be securely held in place should all be noted. Fig. 223 shows some of this in detail.

152. Three-phase Armature Winding.—In Fig. 224 the ends of several wires are shown placed at regular intervals around the armature of a revolving field alternator. *a, d, g* have maximum e.m.f. in them; *b* and *e* have a small e.m.f. increasing in amount for the direction of rotation shown, while *c* and *f* have a small e.m.f. diminishing in amount so as to be zero when these wires are midway between tips of adjacent poles. *a* and *d* are in proper relation to become the places for sides of a generating coil. If *b* and *e* are made the sides of another coil and *c* and *f* of still another, three coils are placed properly to form the first of each of the three sets of a three-phase armature winding. Consider Fig. 225. At the instant represented in Fig. 224, conditions are represented at the intersecting line *SS*. Coil *a* to *d* is the *A* phase, *b* to *e* is the *C* phase, and *c* to *f* the *B* phase. When this principle is elaborated to show a two-layer distributed winding in a slotted core the appearance would be like that shown in Fig. 226. This figure shows two slots per phase per pole. A formed coil is placed with one side in the bottom layer in slot 1, the other side being put in the top layer in slot 7. All the other coils are placed in a corresponding way. When cross-connections are made, they are managed as shown. Take the *A* phase. Starting with one end (*a*) of the coil just referred to, the winding passes through all the turns of the coil to *b*; thence

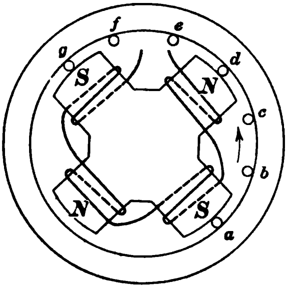


FIG. 224.

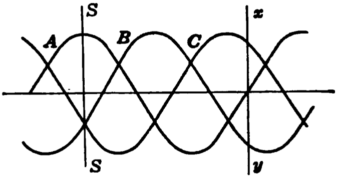


FIG. 225.

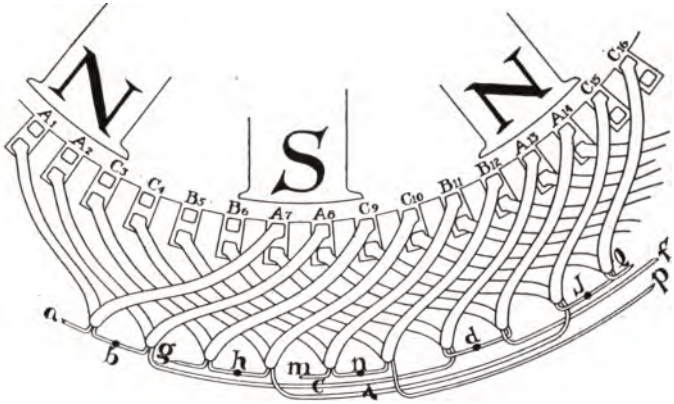


FIG. 226.

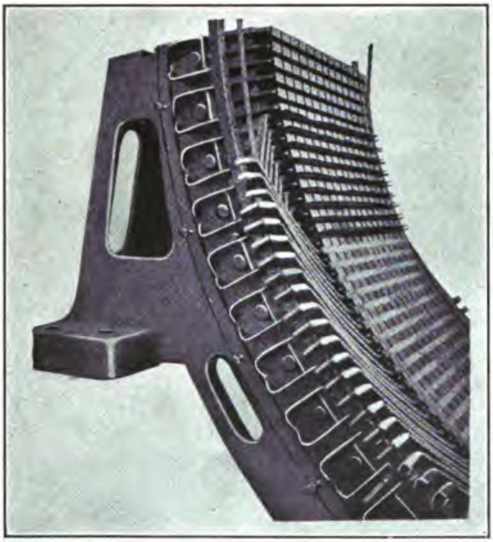


FIG. 227.

a soldered connection to the next coil which completes the set in this phase at this place. From this by wire *C* we pass to a wire of a coil in the top layer of slot 13, thence to the bottom of slot 7, through all the turns of that coil, on to the next one through a soldered connection at *d*, on through the next coil, and so on. When the three sets of coils are all connected together there will be six ends. Y- or Δ-connections are commonly made among the ends and only three lines carried from the machine. The same precautions in making the interconnections must be taken as described when discussing transformer connections (sections 143 and 144). In Fig. 227 is shown a three-phase armature winding for a revolving field machine. Should a revolving armature be used, the connections would be very similar and the number of slip rings required would be regulated by the arrangement of the interconnections. It might be noted that when an armature is Δ-connected the current in any lead from the machine is 1.73 times as much as that flowing through any one of the sets of coils on the armature.

153. Alternators in Parallel.—Alternators are connected in parallel to serve constant-potential circuits for the same reason that D.C. machines are so connected. It is much more difficult to put them in parallel for the very reason that they generate alternating e.m.f. The e.m.f. reverses every $1/120$ sec. on a 60-cycle machine, and if the circuit is closed when the e.m.f. is the wrong way the instantaneous result would be similar to that which would happen if when putting two D.C. machines in parallel one has reversed polarity. In what follows single-

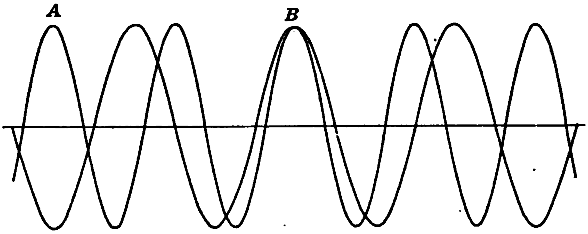


FIG. 228.

phase machines only will be considered. Polyphase dynamos would be put in parallel the same way, but in first arranging the switchboard connections each phase must be considered separately. When two alternators are moving at as nearly the same speed as possible, their individual e.m.fs. will be as shown in Fig. 228. At *A* the two are opposite in phase; at *B* they are directed the same way. Under such circumstances if they were connected as shown in Fig. 229 the lamps would light when condition *B* was reached and be out, because there was no current in them, when condition *A* was found. Hence the lamps would light at intervals. When they were out the dynamos might be connected together (that is, for parallel operation) by closing the short-circuiting switch *S*. If a load were connected between *a* and *b* it would be supplied from the machines in parallel.

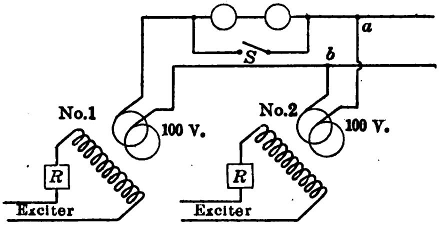


Fig. 229.

The process of getting alternators to have the same frequency is called "bringing them into synchronism." That of getting them into opposite phase with regard to each other as indicated by the lamps is "getting them into step." Lamps furnish the simplest device for bringing machines into synchronism and into step; other devices are also used.

After alternators are connected in parallel they hold each other in synchronism and in step by an interchange of current between them. If one machine starts to drop out of proper phase relation the difference in e.m.fs. immediately causes a current to flow which pulls them back into step. In any normal case this interchange of current should be quite small. In Fig. 230 a set of connections is shown for parallel connection of alternators the synchronizing lamps being connected on the secondaries of transformers. This is done to reduce the voltage on the lamps and sometimes so that the synchronizing can be done with the lamps lighted. The process of putting two machines in parallel is as follows: Machine No. 2 is supplying the load and its main switch is closed, while that on No. 1 is open. Bring No. 1 up to voltage. Close a switch on the synchronizing circuit (not shown in diagram). If the machines are running at nearly the same frequency the lamps light up, then go out, light up again, etc. If the machines are in step with lamps out, wait until they are out for a few seconds and just then close the main switch.

To determine whether the lamps should be out or lighted when the dynamos are in synchronism and in step for a particular set

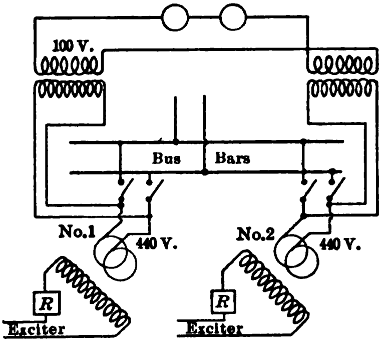


FIG. 230.

of connections, proceed as follows: Lift the brushes of one machine from the collector rings and then with the other machine operating at regular e.m.f. close both main switches. Both transformers now receive current from the same dynamo, and the lamps are either continuously lighted or out. If out, the dynamos are afterward to be put in parallel with lamps out; if lighted, the dynamos are to be put in parallel with lamps lighted. A similar procedure is easily arranged for machines with stationary armatures.

Varying the field strength by adjusting field rheostats will not change the distribution of load on the dynamos. It results only in an interchange of wattless current between the alternators. Adjustment of the engine governors is necessary to alter this distribution.

The importance of balanced load on polyphase dynamos may be here noted. The e.m.f. for all phases is generated by cutting flux of the same set of fields. Hence if on one the voltage drops due to a heavier load coming on it only, nothing to correct it can be done, since an increase of field current will make the voltage on the other phases too high.

154. Switchboard Devices.—The actual switchboard arrangements used with alternators are in many respects similar to those for D.C. machines. Besides an ammeter for each alternator and a voltmeter which can be connected to each, there must also be a wattmeter to show how much power is being developed. If the alternator is three-phase, three ammeters are usual, and either three wattmeters or one three-phase wattmeter. A power-factor meter is also frequently installed and sometimes a frequency meter. Ordinary knife switches may be used for low-voltage machines, and circuit-breakers similar to those for D.C. installations. The rheostat arrangement for controlling alternator voltage by varying D.C. current in the field windings is commonly as shown in Fig. 231. On a common center two handwheels are mounted. One (*A*) controls a rheostat in the exciter field circuit; the other (*B*) one in series with the field winding of the alternator. Should the field excitation be secured

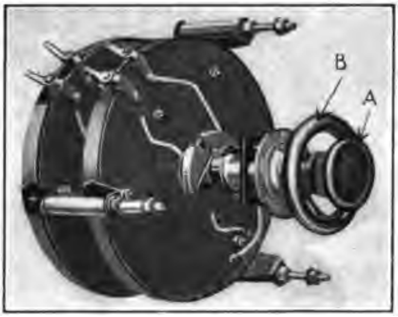


Fig. 231.

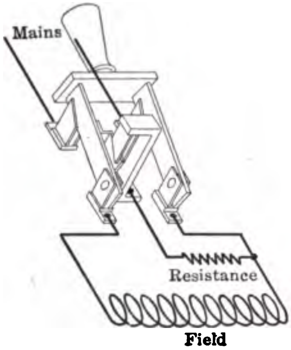


Fig. 232*A*.

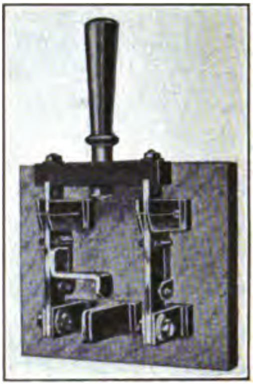


Fig. 232*B*.

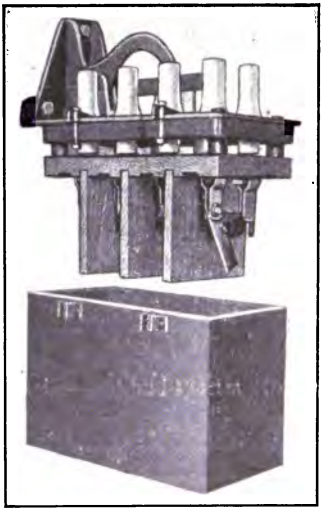


Fig. 233.

from D.C. busbars and not from a separate dynamo for each alternator, a switch is installed by means of which the field current can be cut off. Such a switch is shown in Fig. 232 along with a diagram to show the manner of disconnection. As the switch blade in diagram is moved in the direction of opening, a connection is formed through which the induced voltage in the field can spend itself as the current there dies out.

Often oil switches are found controlling the main circuits on A.C. boards. Fig. 233 shows one of a simple form mounted on the back of a switchboard. The oil tank is dropped to expose the blades and baffle plates, etc. An up-and-down movement of the switch handle on the other side of the switchboard closes and opens the switch. Circuit connections are made through lugs enclosed by the porcelain bushings. The oil serves the purpose of disrupting the arc at break, and of diminishing the necessary distance of separation of the switch contacts. With such a switch the live connections are all out of reach and fully enclosed.

On high voltage A.C. switchboards the arrangements are so complicated by the dangerous voltage and the necessary spacing of apparatus, etc., that use is made of remote control, instrument transformers, and many special devices the description of which may be found in books devoted to such subjects.

QUESTIONS AND PROBLEMS

1. A 2000-volt alternator having 12 poles runs at 1200 r.p.m. What frequency will it have? If the field excitation were kept constant and the speed dropped to 600 r.p.m., what would frequency and e.m.f. become? How many degrees of rotation are passed through for a cycle to be completed?

2. A certain alternator has 40 poles and runs at 75 r.p.m. It generates 6600 volts. What is the frequency? How many volts and what frequency if the flux be cut to 80 per cent. of its former value?

3. A 16-pole alternator has a coil armature like that of Fig. 209 or 211 in the text. If operating at 450 r.p.m. how many volts are generated per coil if all are in series for 2000 volts, and what is the frequency of the A.C.? How many volts will be generated and at what frequency if the coils were changed from one series to a connection in which there are four parallels of four coils each?

4. An alternator is operating a load of 30 kw. at 1000 volts. It has a winding connected in two parallels. The power factor of the load is 0.9. Calculate the current in any wire of the winding. The machine makes 900 r.p.m.

5. Two alternators exactly alike have six poles each. When running at 900 r.p.m. one has a certain point on the armature 10° ahead of the corresponding point on the other. What difference in phase in the e.m.fs. they generate?

6. A 10-pole alternator with rotating armature, has a coil armature winding having one slot or one coil per pole. Each coil has 80 turns and the machine is operated at a frequency of 60. The flux out of or into each pole is 2,500,000 lines. The number to reduce average e.m.f. to effective (K in the formula) is 1.2. Calculate the effective value of generated e.m.f. of the alternator.

7. An alternator similar to that in problem 6 is under consideration. In reference to it state and explain the result of (*a*) running with reversed rotation, (*b*) swinging the brushes around the collector rings. If this machine (10-pole) is generating 1080 volts, how could the winding be rearranged so that it would generate 216 volts. Show by a diagram the supposed connections between armature coils (*a*) before the rearrangement, (*b*) after the rearrangement.

8. (*a*) An alternator like that of problem 6 is running with a generated e.m.f. of 2200 volts on 55 kw. produced. The resistance of the armature is 1.3 ohms. Only 2060 volts are observed at the terminals. Explain. (*b*) Starting from no load the terminal volts with increasing current and fixed field excitation are as follows.

Volts	Amperes
2400	0
2370	5
2345	10
2320	15
2290	20
2260	25

Is this a normal machine? Give reasons for the readings.

9. Two alternators are built to operate in parallel. They are exactly alike and have 10 magnet poles. In regard to them answer the following:

(*a*) One is running at 720 r.p.m.; the other at 723. Calculate the frequency of both machines and tell how long a time passes from the time when the synchronizing lamps are dark until that when they are most bright.

(*b*) What would result if the two machines were put in parallel when exactly out of step (that is, differ in phase by 180°)? (In answering this remember that alternator armatures necessarily have a high inductance and on short-circuit not only is the inductance the main factor in determining the amount of current but the current will lag far behind the generated e.m.f. Refer also to Fig. 215 in the text.)

10. Make a diagram to show how connections would be made for the field circuit of an alternator. The field is supplied by current from an exciter driven from the shaft of the alternator, a double rheostat like Fig. 231 of the text being in use.

11. A certain two-phase alternator has a stationary armature arranged like that shown in Fig. 221. The machine has eight poles and in each phase the coils are connected in two parallels. The alternator is marked 100 kv.a. at 2000 volts. How many coils on the armature? How many amperes flow through and how many volts generated in each coil under full-load conditions? Neglect volts lost in getting the current through the impedance of the winding.

12. A three-phase alternator arranged with armature winding like that of Fig. 226 has the coils arranged so that in each phase there are two parallels. The machine is for 120 kv.a. at 1000 volts. It has 10 poles. How many coils are used for the whole armature winding? How many amperes flow through each coil, how many in each alternator lead and how many volts does each coil supply (*a*) when there are three collector rings and the armature is Δ-connected? (*b*) when with three collector rings the armature is Y-connected? Neglect armature drop of potential under load.

CHAPTER XIV

ALTERNATING-CURRENT MOTORS

155. Types of Motors.—There are several types of A.C. motors which are in common use. They will be named here, but their method of operation and their applications will be separately described later.

1. *Single-phase Series Commutator Motor.*—These are practically the same as D.C. series motors in general features of construction and performance.

2. *Synchronous Motors.*—They are alternators, either single or polyphase, operating as motors.

3. *Polyphase Induction Motors.*—When A.C. is introduced to them, a rotating magnetic field is produced; as a result of which a drag is set up between the field and the current induced in a short-circuited winding on the rotating element.

4. *Single-phase Induction Motors.*—Belong to the same general class as No. 3 but have special means of securing a rotating torque.

5. *Synchronous Converters.*—A kind of synchronous motor arranged mainly for the purpose of transforming A.C. to D.C.

156. Series Motors.—If a D.C. series motor has the direction of current through it reversed, it continues to move in the same direction as before. Since the direction of current has no relation to rotation, it is evident that a current periodically reversed would be satisfactory for driving the machine and this is just what an alternating current is. Almost any small D.C. series motor will run "free" if A.C. is used on it; but it will not carry any load and is apt to spark badly at the brushes even though a very small current is flowing through it.

A motor built for D.C. has so much impedance in the field that the application of doubled A.C. voltage to the machine will not admit enough current to produce much turning effort. Small motors of this kind ($\frac{1}{20}$–$\frac{1}{10}$ hp.) are made to operate on either

A.C. or D.C.; but when operated on A.C., connections are made through a special tap which cuts out of circuit quite a part of the field winding. The cause of sparking at the brushes may be seen by referring to Fig. 234. As the armature revolves coil after coil is short-circuited at each brush; coil 2 is short-circuited in the figure. Suppose just now the A.C. is diminishing through the field windings. The flux from *N* to *S* through this coil is diminishing and so an e.m.f. is generated there which through the very low impedance of a single coil, may send quite a current through the short-circuit by way of bars *a* and *b* and the brush. As coil 2 moves on and bar *b* leaves the brush tip, a spark forms as the short-circuit opens. In small machines by multiplying the number of coils in the armature winding, and so the number of commutator bars, far above the number usual on D.C. machines this can be partly suppressed.

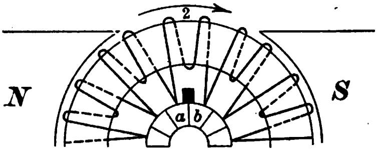


Fig. 234.

157. Uses for Series Motors.—There are a great many applications in which the convenience of being able to use the same motor on either A.C. or D.C. is such, that the disadvantages of the series motor do not keep it from use. Such motors can be purchased in the small sizes named above. They are used for operating small vacuum cleaners, small office appliances, dental engines, etc. Very few makers build them. In starting, these little motors are commonly put directly across the line. Sometimes they are started and controlled in speed by the use of resistance in the circuit the same as for D.C. motors.

The same motor has also been perfected for railway service by the engineers of the Westinghouse Company. Many large locomotives and interurban cars operate with these motors under them; some operating on parts of the road with A.C. and on other parts with D.C. The difficulties to be overcome in large motors are very much greater than in small ones and a higher frequency than 25 is never employed. The power factor is always low. In starting, transformer devices are always used so that when a heavy current for initial pull is required, it is received at low voltage and the main-line current thus kept low. Controller arrangements as complex as those used with D. C. railway motors are used in operating them.

The motors described in this section operate only as single-phase machines.

158. Synchronous Motors—Principle.—In an ordinary D.C. motor the current reverses in any conductor as it passes from before a *N* pole to before the next *S* pole. This is done by means of the commutator and brushes, in order to have the pull for rotation which it produces continue in one direction. In Fig. 235 this is shown; the arrow gives the direction in which conductors in the two positions shown will pull when carrying current as marked. Suppose now an alternating current admitted to that one of these conductors now under the *N* pole with current directed outward, and that the reversals of A.C. are so timed with the rotation of the armature that when an alternation is completed the same conductor is in the position marked *b* under the *S* pole. It will be clear that the pull for rotation under these conditions would continue the same way. When a machine is running at such speed that the alternating current in the armature winding reverses in time with the advance of a particular part of the winding from pole to pole, it is said to be at synchronous speed and the motor running thus is said to be a synchronous motor.

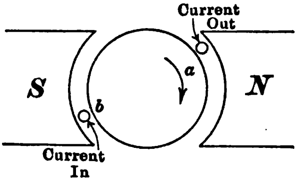


FIG. 235.

It has already been shown that an alternator operating on inductive load works during part of each cycle as a motor (section 121). Alternators will run as synchronous motors when connected to supply lines and not driven by some motive power. Synchronous motors are either single or polyphase alternators used as motors. Polyphase machines are much more common than others but since it is easier to think of single-phase machines their performance only will be taken up.

It should be noted that in the previous discussion a fixed direction of flux from the field is assumed. Hence a D.C. machine must always be available to supply field current for a synchronous motor just as it is for any A.C. dynamo.

159. Synchronous-motor Operation.—The pull for rotation in an A.C. motor is due to the same causes and varies the same way as in a D.C. motor. The e.m.f. which sends the current through the armature is not the applied e.m.f. but is that due to the applied e.m.f. and motor e.m.f. (back e.m.f.) together. Suppose the synchronous motor to have the same e.m.f. as the supply line, to be running at the same frequency, and to be in opposite phase. If then the circuit were closed no current would flow, for there would be no e.m.f. to send it (see Fig. 236).

Now if the motor e.m.f. drops back in phase a little (time is going on and the applied e.m.f. line is therefore further on) the relation between the e.m.fs. will be as in Fig. 237. There will then be an e.m.f. to send the current, marked circuit *E*, and a current for rotation flows. If this drives the load the motor runs on synchronously, for if the motor surges ahead things return to conditions in Fig. 236, the current diminishes and the pull for rotation is cut off; while if the motor drops back in phase the circuit e.m.f. becomes still larger and an extra pull is created to bring back the proper phase relations (see Fig. 238).

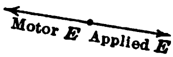


Fig. 236.

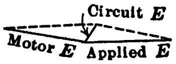


Fig. 237.

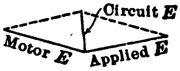


Fig. 238.

If a heavier load is put on the machine the motor cannot slow down, for if it did it would stop, since the torque produced in it would not keep continuously in one direction. What happens is this: The application of more load finds the motor unable to supply the torque demanded and it begins to stop. But before the armature has settled back more than a few degrees from the position where it would have been had absolutely uniform rotative speed continued, the changing phase of its e.m.f. has given the circuit e.m.f. a large enough value to let current flow to the required amount. This is shown in Fig. 238 (compare Fig. 237).

This way of assuming load may be made more clear by a study of a mechanical illustration given in Fig. 239. Suppose flywheels to be mounted on the ends of two shafts so that the connection between them is simply a straight steel spring as shown. At *A* is shown the condition when the driven shaft has no load upon it. When the load gets heavy on the driven shaft, the relative positions of the wheels are as shown at *B*. The r.p.m. of the driven wheel are still exactly the same as that of the driver; it has simply dropped back in phase.

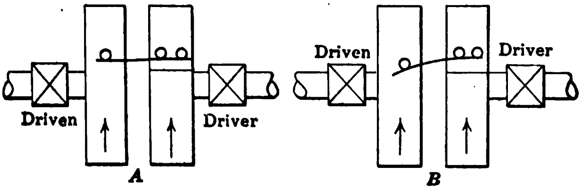


Fig. 239.

At some overload the motor must drop out of synchronism and stop. This is usually not before 50 per cent. overload is reached. Up to that time no change of load will change the speed a particle. Nothing except a variation in the frequency of the supply can alter that.

160. Synchronous-motor Current.—Since the circuit through which the circuit *E* of a synchronous motor sends current is sure to be quite inductive, the current will lag behind this e.m.f. a considerable amount. Referring to Figs. 237 and 238 it will be seen that this would bring the current quite nearly into phase with the applied e.m.f. Hence the power factor of such motors is usually quite high.

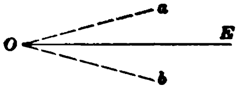


Fig. 240.

Further, the current may lag behind the applied e.m.f. or lead it. In Fig. 240 two current lines are shown, *oa* being one which leads the e.m.f. *OE* a certain angle; *ob* being an equal current which lags behind *OE* an equal amount. The power factor of a circuit having this e.m.f. applied would be the same for either of the currents. For many practical purposes it is an advantage to have the current lead the applied *E*, since a leading current in one branch of a circuit combines with a lagging one in another to produce a total current more nearly in phase and so the power factor of the main line is improved. Varying the amount of D.C. in the motor field will affect the phase relation of applied e.m.f. and current, also the amount of current which flows for a given load. For to develop a certain amount of power, more and more current has to flow as the current goes farther out of phase with the applied e.m.f.

Single-phase synchronous motors produce a pulsating pull for rotation since there can be no pulling effort at those instants of time when the current passes through zero. Polyphase motors produce a rotative pull quite nearly uniform because the pull, due to current in each of the phases, becomes zero at different times. Refer to figures showing polyphase armature windings to make this more clear.

The pulling effort exerted in a synchronous motor is not proportional to the amount of current flowing, mainly because of the various possible relations between the instant of maximum current and the point of rotation of the armature reached by that time.

161. Starting Synchronous Motors.—Such motors cannot be started by being directly connected to the line, for on turning current on there would be a pull in one direction followed by an equal pull in the other, and so no rotation could result. They must be brought to speed by some special starting device. When at synchronous speed they must be synchronized and put on the A.C. supply precisely in a similar way to that used when putting A.C. dynamos in parallel. They should be in exactly opposite phase to the dynamo supplying them with current when thrown on the line. If not, a large synchronizing current passes through the machines, which spoils the regulation of the dynamo and dims the lights on the system, as the motor is jerked into proper phase relation with the supply.

Synchronous motors may be started by auxiliary A.C. motors of other types which bring them up to synchronous speed before a load is put on them or by running their exciters as D.C. motors from some source of direct current. They should always be started without load.

Another method available for starting polyphase synchronous motors without the use of auxiliary motor devices or synchronizing is referred to below in section 178, part C.

162. Uses of Synchronous Motors.—It is unusual to find small synchronous motors in use. The difficulty of starting them, and especially the need of starting without load and the necessity of a direct-current supply for the fields makes them undesirable.

Large synchronous motors are used on many long-distance power transmission lines because they have exactly constant speed and are well adapted for driving certain kinds of machinery. Current is often brought to them and used without transformation at 6600 volts or even more.

Sometimes they are selected in preference to other motors in order to assist in improving the power factor of the line.

163. Polyphase Induction Motor.—The motor to which polyphase currents are especially adapted is the induction motor. All the wires of a two- or three-phase line are brought to them. Polyphase alternating-current systems are installed mainly so that induction motors can be made use of.

Induction motors have two parts: the stationary structure corresponding to the field of a D.C. motor, called the stator; and the rotating structure corresponding to the armature of a D.C. motor, called the rotor. Into the windings on the stator the polyphase currents are introduced; they are called the primary windings. The windings on the rotor then have alternating currents induced in them and the flow of these currents in the secondary windings gives the means whereby turning effort is secured. A rotating field is set up by the primary winding which drags the rotor after it.

It is possible to put the primary windings on the rotor and have the secondary winding on the stator, but it is an unusual arrangement.

164. Rotating Field.—Polyphase currents introduced into the windings of an induction motor produce a rotating field. No explanation of the operation of the motor can be made until the rotating field is clearly understood.

A rotating field may be produced by any polyphase current system. The one resulting from the use of two-phase currents is least difficult to describe and will be the only one discussed.

Fig. 241 shows two equal currents with the proper phase relation for a two-phase system. The vertical lines marked 1, 2, 3, 4, etc., designate selected instants referred to in subsequent figures. Each current has a maximum value of 10 amp. Fig. 242 shows field windings such as might be found on the field of a four-pole D.C. dynamo. Connections must be imagined between *a* and *a*; also between *b* and *b*. The path of the current from the *A* phase would be from *A* through the two windings on opposite poles in series to *A′*; the current in the *B* phase flows by a similar path from *B* to *B′*.

Take the instant represented by line 1 in Fig. 241; Fig. 242 shows the conditions. Current in the *A* phase is 0 amp.; that in the *B* phase 10 amp. in the negative direction (the maximum value). Magnetic flux then streams across the interpole space as shown, the finer lines showing the flux distribution. The heavy arrow is to indicate the general direction of the flux. A little later the time represented by line 2 has been reached. Fig. 243 shows the conditions then existing. (Figs. 243 to 246 are simplified from 242 to save space. The same frame and winding connections are shown.) The positive current in the *A* phase has raised to 7.07 amp. and the negative current in the *B* phase has dropped to 7.07 amp. Each winding sends flux across the gap as indicated by the dotted arrows in the figure. These two currents combine together to produce the flux shown by the heavy black arrow, for they may be combined the same way we have

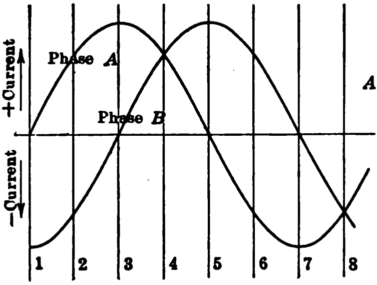


Fig. 241.

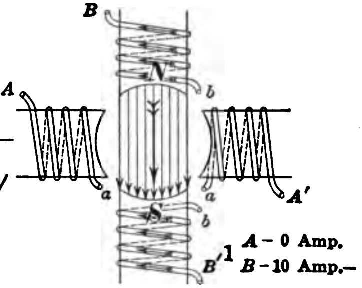
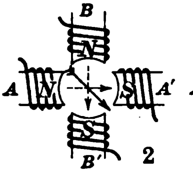


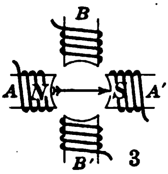
Fig. 242.

been combining currents in diagrams like that shown in Fig. 247. In a corresponding way Figs. 244, 245, 246 are drawn for the instants of time marked by lines 3, 4, 5 in Fig. 241 and the direction of the flux produced is marked by a black arrow. Looking over the set of figures it will be seen that the magnetic flux produced by the two currents acting together has been revolving counter-clockwise and a half revolution has been completed. Something has happened which is precisely the same as though the magnetic circuit shown in Fig. 248, with direct current of fixed amount through the winding as shown, were steadily turned through half a revolution about an axis such as that an armature shaft would represent; in other words, a rotating magnetic field is being produced by the polyphase currents, but without the motion of any material part.



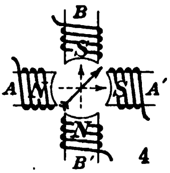
A – 7.07 Amp.+
B – 7.07 Amp.–

FIG. 243.



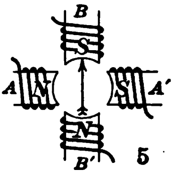
A – 10 Amp.+
B – 0 Amp.

FIG. 244.



A – 7.07 Amp.+
B – 7.07 Amp.+

FIG. 245.



A – 0 Amp.
B – 10 Amp.+

FIG. 246.

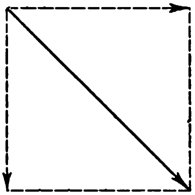


FIG. 247.

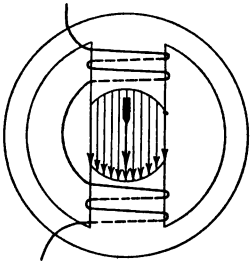


FIG. 248.

Note that in rotating the field half a revolution, either current completed a half cycle. Hence a complete rotation would occur with each complete cycle. A 25-cycle, two-phase current would produce a rotating field making 25 revolutions per second or 1500 per minute.

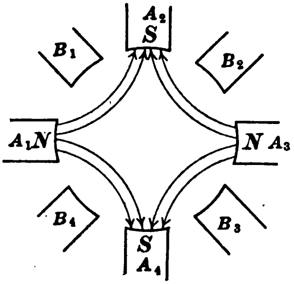


FIG. 249.

165. Practical Rotating Fields.—The rotating field just explained is a two-pole field. It is just as easy to make a multi-polar field. Fig. 249 shows how this could be done. Around the poles A_1, A_2, A_3, A_4 the current from the A phase flows. Flux paths are indicated, assuming that there is current in these coils only. The current in the coils on the poles marked B is derived from the B phase. If Fig. 249 represents the conditions corresponding to line 3 of Fig. 241, when the time represented by line 5 is reached the N pole marked on A_1 will have moved on to B_1 and there will be no flux out of A_1; in other words, during this quarter cycle the rotating magnetic field has moved ⅛ of a revolution. If a 25-cycle, two-phase current were introduced to the windings of such a structure the rotating field would then make 12½ revolutions per second or 750 per minute. It is intended by this example to show that the r.p.m. of the rotating field depend on the number of rotating poles; the more multipolar the slower its speed of rotation.

But in actual machines such projecting poles as shown in Figs. 242 and 249 are not used, mainly because while a rotating field would be produced, the flux path from instant to instant would become very irregular and so the amount of flux be variable. If a construction similar to that shown in Fig. 250 is used coils may be placed as shown in two independent circuits. The parts on which *i* is marked are sheet-iron stampings, a number of which have been assembled above each other so that slots like those for the armatures of revolving field alternator are formed. That circuit from 1 to 1′ might have the A phase connected to it, and that from 2 to 2′ the B phase. The figure shows a condition which results when equal currents are flowing in both phases, as at the time shown along line 4 in Fig. 241. A multipolar field is produced similar to that in Fig. 249. As the currents change a revolving field is produced.

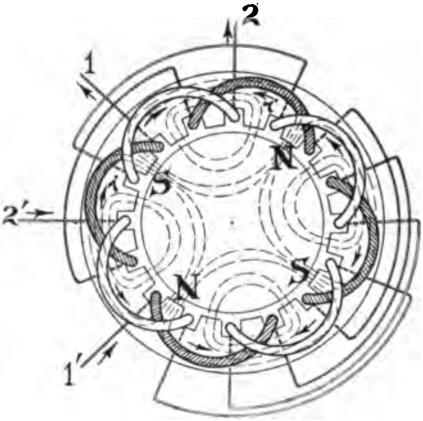


Fig. 250.

166. Commercial Windings for Rotating Fields.—*The Stator.*—In regular practice the winding arrangement is further elaborated so that a group of coils combine to produce each pole. Fig. 251 shows a simple arrangement of such a winding for a multipolar rotating field. A slotted iron structure is shown built up

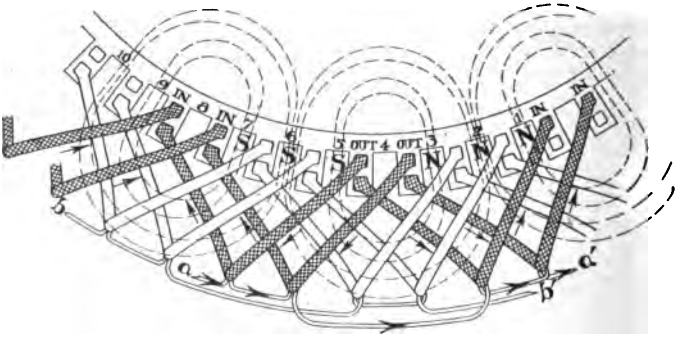


Fig. 251.

like that of Fig. 250. If current flows from *a* to *a′* through the coils as shown, magnetic flux will take the paths marked. Had current been introduced into the other set of coils, flowing from *b* to *b′*, the center of the *N* pole shown would have moved from tooth 2 to tooth 4, and the center of the *S* pole from tooth 6 to tooth 8. If two-phase currents were introduced into both windings, that of the *A* phase between *a* and *a′*, the conditions shown in Fig. 251, corresponds with the time indicated by line 3 of Fig. 241, and that described as existing when current flows from *b* to *b′* corresponds to line 5. The design is such that there would be 56 slots or teeth on the completed structure. Hence $\frac{2}{56}$ of a revolution of the revolving field is completed in a quarter cycle. With this arrangement the number of poles of the rotating field would be 14. Hence the r.p.m. on a 25-cycle circuit would be $214\frac{2}{7}$.

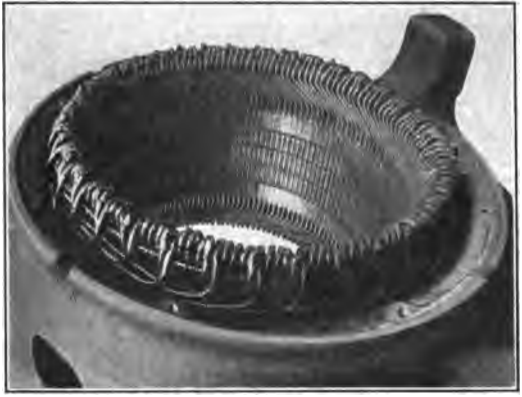


Fig. 252.

It is usual to use more than two adjacent coils to each group. The ends of the coils are not given quite the shape of Fig. 251, but have an easy bend instead of a sharp turn at their ends. A winding like that in Fig. 252 is thus made, the cross-connections between coils being tucked away out of sight. The laminated slotted structure in which the coils are laid with two ventilating ducts is clearly shown. This laminated structure is mounted in a cast-iron frame and held together by end castings, the bolts for securing which are in plain view. This particular motor is a three-phase machine since there are but three terminals (at the right); a two-phase machine would have four. It is impossible from the figure to tell certainly how many coils form a group; there may be four.

At this point it will be well to compare Figs. 221 and 222 with Figs. 251 and 252. The windings are the same.

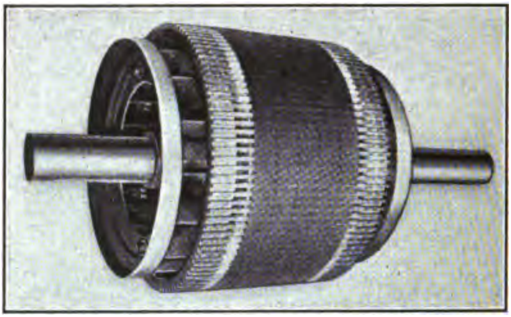


Fig. 253.

167. The Rotor.—Within the stator there is the rotating element of the motor, called the rotor. This is a cylindrical structure built of sheets of laminated iron similar to the armature core of a D.C. machine. The winding on it may be a two-phase or three-phase alternator winding put together for the number of poles the motor has, and ending in slip-rings; or it may be a series of copper bars, one per slot, all the bars connected at each end to a copper ring making a structure like the wheel of a squirrel cage. Fig. 253 shows such a squirrel-cage winding; Fig. 254, a wound rotor probably made with a three-phase winding as this is generally used.

The squirrel-cage winding is so very common that it is mainly considered in the next paragraphs. Its advantage lies in the fact that no brushes or rubbing contacts are made use of. Hence the motor can be put in any location and amid any sort of surroundings. It may be wholly inaccessible except for lubrication.

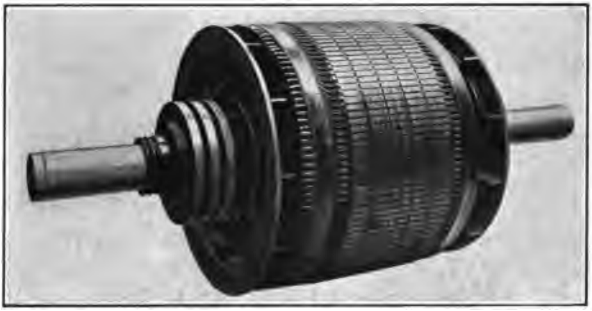


Fig. 254.

168. Principle of Operation.—Think of a squirrel-cage rotor in place within the stator, and polyphase currents flowing in the stator windings to set up a rotating field. The bars of the squirrel cage will have e.m.f. set up in them, larger in some, smaller or nothing at all in others, in one direction in some, in the reverse direction in others. A little thought will show how there will be large currents set flowing, due to even small e.m.fs. generated, in somewhat indefinite paths. Should these currents flow in proper direction and in right relation to the rotating field a pull for rotation will be produced like that in a D.C. motor and the speed would increase up to some steady value.

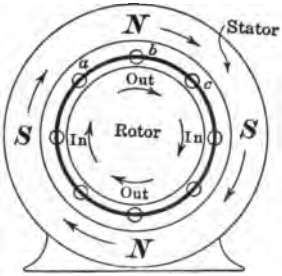


Fig. 255.

Consider Fig. 255. If the field poles are as placed and sweeping onward in the direction marked, e.m.fs. will be induced in bars of the squirrel cage and currents will flow as marked (in checking this remember that rule in section 84 was for moving wires before stationary poles). Using this rule for motor action it will be found that the pull for rotation is that marked on the rotor; that is, the rotor is pulled in the direction the rotating field is moving. If the speed reached the same r.p.m. as the rotating field the rotor is said to be running at synchronous speed. On a 25-cycle circuit a motor with four rotating poles would have a speed of 750 r.p.m.

Think now of conditions in the rotor when at synchronous speed, and go on to understand how the motor operates automatically to control the mechanical power developed and the electrical power supplied. At synchronous speed the rotor would have no e.m.f. in the windings for there would be no cutting of flux by them. If, however, the speed drops a little, a small e.m.f. will be generated and so small currents flow as shown in Fig. 255. A small pull results, and if this is just the right amount to drive the mechanical load a steady speed results. If the rotor is going then at 720 r.p.m. and the stator field at 750 r.p.m., an e.m.f. is generated just the same in amount as though the rotor were at rest and the rotating field were making 30 r.p.m. If the current then flowing does not produce enough turning effort to drive the load the motor slows down a little more, larger e.m.fs. are therefore induced and a larger current would flow. If the speed is now 690 r.p.m., twice the e.m.f. would be generated, twice the current flow and twice the pull to drive the load would be present. Thus every load has a steady motor speed corresponding with it; the larger the load, the slower the speed. This is precisely the same relation between speed and load as that which holds for a shunt motor on D.C.

In the rotor winding the current flowing is alternating and when running at usual speeds it has a very low frequency. Take the motor here in mind, at 720 r.p.m. of the rotor. The e.m.f. generated will have a frequency of 1 for, as explained above, conditions are the same as though the field were stationary and the rotor making 30 r.p.m. $(750 - 720)$, and the machine has four poles. At 690 r.p.m. the frequency is 2. At $^{750}/_{2} = 375$ r.p.m. the frequency is 12.5 cycles per second. This changing frequency which accompanies changing amount of current in the windings plays an important part in motor performance. When the rotor runs nearly at synchronous speed the frequency is so low that in spite of inductance of the windings the current is in phase with the generated e.m.f. and proportional to it. Hence the facts stated earlier regarding increased pulling effort along with increased generated e.m.f. hold good. But at heavy loads with higher frequency of rotor current it lags behind the e.m.f. In an extreme case the *N* pole opposite bar *b* (Fig. 255) might have moved on to be opposite bar *c* before the current, now assumed to be lagging a quarter period, was at its maximum. If so, no rotative pull could be secured. Hence for any motor, at some overload even with large currents in the rotor the motor ceases to pull the load and stops. This is quite different from the performance of D.C. motors, but usually an induction motor will not refuse to pull until 50 per cent. overload or more is reached.

It may be further noted here that in order to produce reversed rotation all which need be done is to arrange things so the rotating field revolves the other way. Referring to Figs. 242 to 246, had the current in either phase been given reversed connections a reversal of the field rotation would have been secured.

169. Induction Motor Performance.—The difference in speed between that of the field and the rotor is called the *slip*. This is usually stated in per cent., the amount being determined from the formula:

$$\frac{\text{Speed of rotating field} - \text{speed of rotor}}{\text{Speed of rotating field}} \times 100 = \text{slip in per cent.}$$

25-CYCLE INDUCTION MOTOR DATA

Horse-power	Number of poles	Synchronous speed	Full load, r.p.m.	Slip in per cent.
3.5	4	750	685	8.7
5	4	750	700	6.7
10	4	750	710	5.3
25	4	750	715	4.7
35	6	500	475	5.0

In the preceding section under one condition the stator field was making 750 r.p.m. and the rotor field 720 r.p.m. The slip was then 4 per cent. The slip found in actual motors may be illustrated by a table in which data from a well-known maker's catalogue is included.

It will be understood of course that, when running free, the motor will have a speed so very near to synchronism that no ordinary method of taking speed will show a difference, and that as the load goes on the slip increases. Note from the table how as motors are of larger size the per cent. slip at full load diminishes.

The performance of an induction motor in many respects resembles that of a transformer. The electrical power represented by the flow of current in the rotor all comes from electrical energy supplied to the stator. The stator winding is a primary to the secondary rotor winding. When, therefore, the mechanical load on a motor increases and the current in the rotor gets bigger, the current flowing in from the supply line also increases. Now in transformers it is desirable to have all the flux produced by the primary to pass through the secondary, and also to have small magnetizing current in order to have a good power factor. Induction motors are planned with air gaps of very short length in order that the distance from primary winding to secondary will be short, and so the magnetic resistance of the flux path will be low.

The efficiency of induction motors is about the same as that of D.C. motors of corresponding size, because of heat loss (I^2R) in their windings, the same iron losses which occur in the cores of transformers, bearing friction and windage.

170. Starting Induction Motors.—Induction motors are self-starting. To start one by simply closing a switch which connects it to the line would produce a result precisely the same as though a transformer having its secondary on a short-circuit were connected directly to a supply. It can be done with very small motors or when a motor of 1 or 2 hp. starts without load, for the period of large flow of current is quickly over as the motor gathers speed. Under overload the motor might not start at all because a pull for rotation great enough to pull the load cannot be reached (see end of section 168).

Two methods of starting are commonly used. One is to use reduced voltage on the motor at starting; this is for motors with squirrel-cage rotors. The other is to put resistance in series with the rotor windings, and this can only be done when the motor has a wound rotor.

171. Starting with Reduced Voltage.—The simplest way to get reduced voltage for the primary stator winding is to put resistance in series with it and so by the *IR* drop use up some of the line voltage. The effect of this is to reduce the current in the motor and so limit the starting pull to a reasonable amount. A starting box used for such work is shown in Fig. 256. It is very much like one used for D.C. motors (compare Fig. 107) but it has a double row of contact buttons and has no automatic release features. The purpose of the double row of contacts will appear from the diagram of connections in Fig. 257 which shows how by swinging the sweep arm clockwise the resistance in both phases is simultaneously cut out. The arm is swung against the restoring force of a coiled spring at the hub and when over to the running position with all resistance cut out a trigger device clearly shown in Fig. 256 holds it there. Automatic release magnets are difficult to design for alternating current.

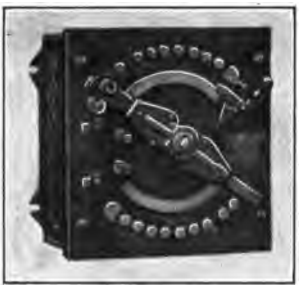


Fig. 256.

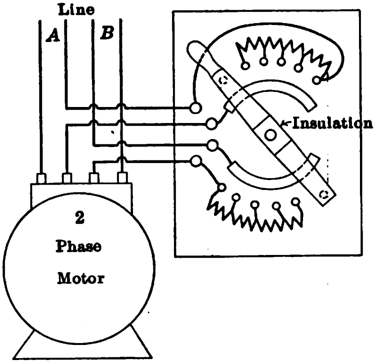


Fig. 257.

Drum controllers are used for the same purposes and self-starters similar to those described for D.C. motors in section 99.

Another way to secure reduced voltage for the stator is by the use of auto-transformers or starting compensators. By using a tap halfway along the winding of such a device half voltage can be secured (see Fig. 179). The results of using such a compensator so far as the motor is concerned are the same as when a rheostat is used, but without the power loss involved and with far less current drawn from the line. Fig. 258 shows a picture of such an auto-starter. Inside the cast-iron box immersed in oil are two auto-transformers and the switch contacts. The switch is a double-pole, double-throw, having two sets of oil immersed butt contacts which close against the pressure of coiled springs.

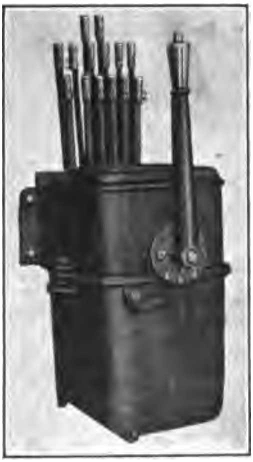


Fig. 258.

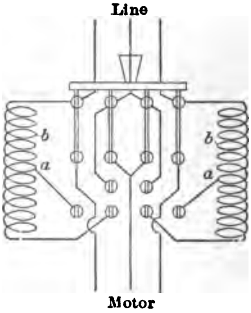


Fig. 259.

The handle is shown locked in the "off" position. Throwing it one way closes one set of contacts, throwing it the other way closes the other. Fig. 259 shows a diagram of the electrical connections of one precisely similar except that an ordinary knife switch is shown. In the position shown the motor is connected direct to the line. If thrown over to starting position the two auto-transformers (one for each phase) have their windings thrown across the mains and the secondary circuit is connected to the motor. The taps marked *a* can be connected at different points so that different e.m.fs. are delivered to the motor and so the amount of starting torque controlled.

Still another plan is used for controlling the applied e.m.f. to a three-phase induction motor. A star-delta switch is used the plan and purpose of which can be seen by inspection of the diagram of Fig. 260. When the triple-pole, double-throw switch is thrown down, the transformer secondaries are connected star. When thrown up they are connected delta. If, therefore, the secondaries each produce 220 volts the motor would receive 220 volts when the switch is up but only $^{220}/_{1.73}$ or 127 volts when it is down.

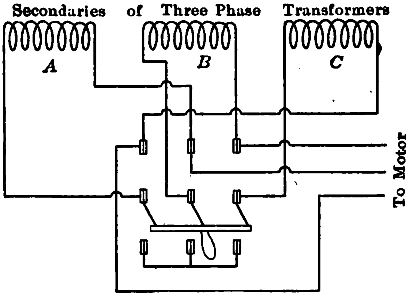


Fig. 260.

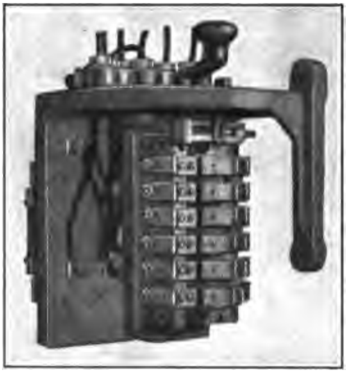


Fig. 261.

In every case the star-connection gives 58 per cent. of the delta-connection voltage to the motor. Fig. 261 shows a drum type of star-delta switch arranged to be operated under oil. Behind the slate backboard shown, the enclosed fuses for the motor are mounted. By this plan the need for an auxiliary auto-starter is avoided.

172. Starting with R in Rotor Circuit.—This method uses the type of rotor shown in Fig. 254. The winding is likely to be that of a three-phase alternator having the same number of poles as the motor and if connected star the three ends would be connected to the three slip rings. From them the connections run to the starting box. Fig. 262 shows a diagram for and Fig. 263 a picture of such a starter. The starter never opens the rotor circuits. At the position shown all the resistance of the box is in use. When the handle is moved to the right, resistance is cut out and at the limit of its motion the rotor winding is short-circuited.

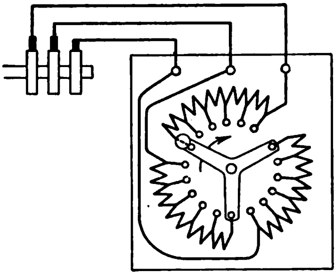


Fig. 262.

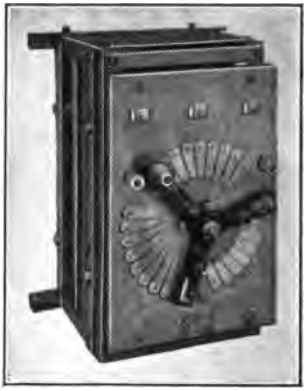


Fig. 263.

If a motor is started with resistance in the rotor circuit the line current is left small since the secondary, the rotor winding, has its e.m.f. sending current through considerable resistance and so the amount flowing is limited. But further, the rotor has at starting an e.m.f. generated in its windings which has a frequency the same as that of the supply line. The interposition of resistance keeps the current flow nearly in phase with the generated e.m.f. and so a high starting torque is secured.

173. Speed Regulation for Induction Motors.—Any induction motor can have its speed controlled by the methods described in the preceding sections. The insertion of resistance in the rotor circuit will reduce the speed for larger e.m.f. must be generated in the rotor winding to secure the same current flow and so the same pull for rotation. Larger e.m.f. is generated only when the slip is greater; that is when the motor runs slower. Reducing the applied e.m.f. will also reduce the speed since smaller flow of current results; hence less flux in the rotating field and less generated e.m.f. in the rotor at the same slip. To keep up the same pulling effort, the rotor must slow down so a larger current is flowing in it; enough to produce the proper rotative pull in spite of the weakened field.

Either of these methods, however, has the disadvantage of giving the motor large *change* of speed under change of load. If under full load a motor is running at half its usual speed due to the use of a rheostat or compensator, arranged to carry the necessary current continuously, at light load the speed would rise to nearly the usual amount.

The only other ways to control speed are to vary the frequency of the supply or to vary the number of rotating poles. It is not convenient to vary the frequency of the supply, and a motor designed for a certain frequency works badly on a different one. The limitations of speed change can be readily seen by the table (p. 268) which gives the synchronous speeds from which the actual speeds would differ by a very few per cent. It should be noted in connection with this table that manufacturers can only supply induction motors to run at certain fixed speeds. Shifts to change the number of poles can be made by the use of a drum controller having proper contact devices. A four-point controller might change the number of rotating poles from four, to six, to eight, to twelve thus changing speeds from 1800 to 1200 to 900 to 600 on a 60-cycle circuit. The extra complication of this arrangement has prohibited the use of such motors except in a few special cases.

POSSIBLE R.P.M. FOR MOTORS AT FREQUENCY OF

Poles	25 Cycles	60 Cycles
2	1500	3600
4	750	1800
6	500	1200
8	375	900
10	300	720
12	250	600
14	214 2/7	514 2/7
16	187½	450

174. Single-phase Induction Motors.—A rotating field may be produced by the use of current from a single phase A.C. supply, if the stator windings of a two-phase motor (see Fig. 242) are so arranged that the current in one (*AA′*) is out of phase with that in the other (*BB′*). They must be connected in parallel from the same supply but in one path by deliberate design as much inductance as possible is included, while in the other as little inductance but as much resistance as possible is placed. The current in one path is then considerably out of phase with that in the other and a rotating field of irregular and imperfect sort is produced. The same result can be secured if a three-phase stator winding is connected to a single-phase line using proper auxiliary resistance and inductance. In such a field a squirrel-cage rotor

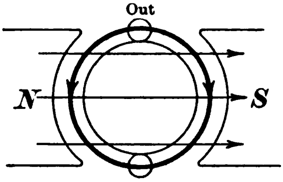


FIG. 264*a*.

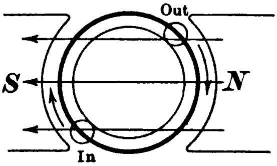


FIG. 264*b*.

will run, but a large current flows to produce a moderate turning effort.

After a squirrel-cage rotor has gained some speed in a rotating field it will continue to run even though one of the circuits be interrupted and a single-phase pulsating field only is available. Thus in Fig. 264*a* is shown the outline of a two-pole motor with squirrel-cage rotor for which only two bars are shown connected into the end ring for simplicity. We are thinking of a time when the current is diminishing in amount and the flux from left to right is almost nothing. It is then *changing* most rapidly through the short-circuited turn and so maximum e.m.f. is generated. If now the rotor is moving fast enough clockwise so that the position shown in Fig. 264*b* has been reached as the current producing the field reverses and is increasing, while the current in the rotor winding due to inductance there is just reaching its maximum, a pull for continued rotation in the same direction is produced (use Rule of section 84). Completing the rotor to make it a full squirrel cage, and winding the field as in Fig. 250 or 251, but with a single winding, would make the motor more complicated to describe but better in operation. Such a motor once started in a given direction will continue to run that way and does not vary speed much under changing load.

Both the principles described in this section are often combined in a single motor. The motor starts as a "split-phase" motor using windings and rotary field as first described. Having reached a fair speed, either by a double throw switch or by a switch and clutch device in the motor, operated automatically by centrifugal force, one winding is cut out and the motor continues to run as a single-phase machine.

Because of limited starting effort, such motors frequently have the rotor mounted "free" on the shaft; and it is not until a fair speed is reached and a centrifugal device operates a clutch, that the shaft and the load connected to it are started. By so starting, the disadvantage of a very low power factor and large current to produce the starting pull are avoided.

Still another principle used in A.C. fan motors on single-phase circuits is that in which a shading coil on the poles is used. A shading coil (marked *S* in Fig. 265) is a band of copper having very low resistance placed around one-half the laminated iron pole. The alternating current in the field winding produces an alternating e.m.f. and current in this short-circuited secondary. When the current is rising to make this a *N* pole, e.m.f. is generated in the band in the direction marked and current flows so that much more flux comes out of the half *a* than out of the half *b*. But later when the current in the field coil is dying out the current in the shading coil is the other way; and so there is more flux in the half *b* than in the half *a*. The result is that the field shifts along the face of the pole with every alternation and an impulse for rotation is given the squirrel-cage rotor much the same as that given a mechanical device in which a pawl working over a ratchet wheel is the means of propulsion.

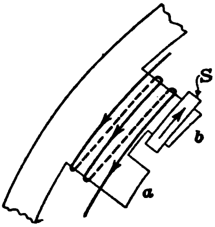


Fig. 265.

175. The Repulsion Motor.—In Fig. 266 is a diagram intended to show the principle upon which this motor operates. The armature is precisely the same as that used for D.C. machinery, shown here as a ring armature only to make the connections and flow of currents clear. A laminated iron structure has field coils placed on it, through which single phase A.C. flows. Brushes rubbing on the commutator are short-circuited to each other and are placed somewhere between the lines *xx'* and *y'y*. It is assumed in the figure that the armature is at rest. The e.m.f. is due to transformer action, current in the field coils *FF'* being in the direction marked and just now decreasing in amount. At *f* the arrow outside the armature is intended to indicate the direction of e.m.f. generated in the coil, as the arrows on the turns or a direct analysis will indicate. On the turns of coils *a*, *b*, *c*, *d*, *e*, the direction of current flow is marked for the direction of e.m.f. just now generated, which the arrows outside the armature on each coil show. If the figure is carefully examined it will be found that the current in the coils short-circuited by the brushes is in such a direction that they are repelled from the poles and the armature would be driven clockwise; but the flow of currents in all the other coils pulls for rotation counter-clockwise and it is in that direction the armature rotates. On account of this differential pull in different coils the brushes are made thin so not more than one coil under each brush pulls against the prevailing pull of all other coils on the armature.

In such a motor there exists a heavy pull for rotation at start although the power factor is low. The motor has a speed as variable with change of load, however, as a D.C. series motor. One way in which this principle is applied in practice to secure a satisfactory motor is to arrange it so that as it speeds up a centrifugal governor is brought into operation which drives a short-circuiting band against the commutator and at the same time raises the brushes. With all the commutator bars short-circuited together the motor runs as a single-phase induction motor, has its nearly constant speed under changing load, and a satisfactory power factor.

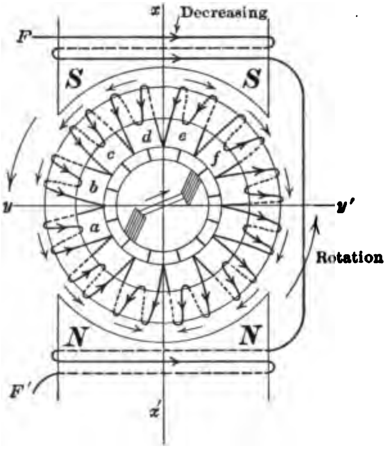


Fig. 266.

Another plan of construction is to have on the commutator an additional set of brushes which are connected with an auxiliary field. These brushes give a means whereby current derived from the armature e.m.f. is used in this auxiliary field to improve the power factor and give the motor a more constant speed.

To reverse rotation of a repulsion motor it is only necessary to swing the short-circuiting brushes to the other side of line *yy'* (Fig. 266).

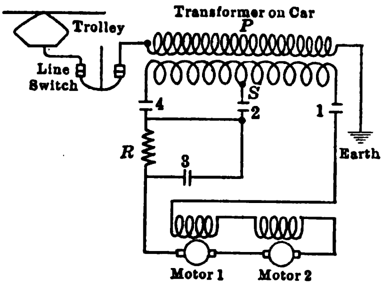
QUESTIONS AND PROBLEMS

1. Thinking of a commutator motor with series field, answer the following: (*a*) If the supply wires were given reversed connection to the binding posts of the motor, how would it perform? (*b*) Give as many methods as you can, using diagrams to show how to reverse its direction of rotation. (*c*) What is the effect on the operation of putting resistance in series with such a motor?

2. (*a*) It is stated in section 156 that when a small series motor used on both D.C. and A.C. is shifted to an A.C. circuit, part of the field coil windings are left out of circuit. Why? (*b*) State any advantages and disadvantages you can in the use of series motors on A.C. circuits.

3. On a certain railway car series A.C. motors are wired for connection as shown in this diagram. Switches are closed according to the following sequence:

First position for starting:
    1 and 2 closed
Second position:
    1, 2, and 3 closed
Third position:
    1 and 4 closed
Fourth position for running
    1, 3 and 4 closed

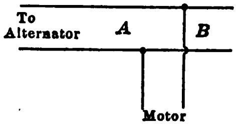


Can you explain the reason for such a set of connections?

4. If you were about to connect a synchronous single-phase motor to the supply line which is 1100 volts, (*a*) at what e.m.f. would you think best to set the motor? (*b*) What would you think of placing it at 1100 volts? (Refer to Figs. 236–238 when answering.)

5. A six-pole, single-phase synchronous motor is connected to a 1000-volt, 25-cycle A.C. circuit. It is marked 100 hp. and is known to have 90 per cent. efficiency. The armature resistance is $\frac{1}{10}$ ohm. What is the current at full load if the power factor is 0.9? What is the speed at no load? At full load?

6. How would you get the direction of rotation of a synchronous motor reversed? Would resistance in series with the armature reduce the speed? If the motor field is strengthened until a current of 40 amp. is flowing, leading the applied e.m.f. of 10,000 volts by 30°, what will be the amount and phase of current in that part of line marked *A*, if before connecting the motor that in *B* was 30 amp. lagging 60° (see Figs. 187 and 240.)



7. Using the same method as in Fig. 247, complete the diagrammatic representation of the magnetic field resulting from the combined action of currents in conditions indicated by lines 6, 7, 8 in Fig. 241.

8. Calculate the maximum polyphase induction-motor speeds for motors having 2, 4, 6, 8, 10 or 12 poles when the frequency of the supply is 30 cycles.

9. A two-phase 5-hp. induction motor has eight revolving poles. At full load the power factor is 0.85, the efficiency is 80 per cent., and the speed of the motor 830 r.p.m. on a 60-cycle circuit. Calculate the slip in per cent. and the current flowing in each of the wires supplying it with current. It is on a 200-volt circuit. What size fuses should be used for this motor? How could rotation be reversed? Make diagram showing how to do it on the actual motor.

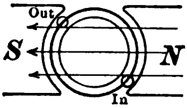
10. A three-phase 20-hp. induction motor under a certain load on a 500-volt circuit makes 570 r.p.m. The supply line is at a frequency of 60 and the current over each of the three wires is 12 amp. What number of rotating poles has the motor? Is it at anything like full load? What capacity fuses should be put into the three-line wires to properly protect the motor? (The efficiency will lie between 90 and 95 per cent. and the power factor will be near 0.9. Remember that there are three windings in the motor to each of which ⅓ the whole power is supplied.)

11. Considering the method of starting an induction motor illustrated by the apparatus shown in Fig. 256 and that in 258 state relative advantages and disadvantages including consideration of power factor and amount of current used.

12. For certain polyphase induction motors the following data is given. The circuit is 25-cycle A.C. at 440 volts. Calculate number of rotating poles for each, per cent. slip, and probably full-load current from a three-wire, three-phase line.

Horsepower	Full load, r.p.m.	Horsepower	Full load, r.p.m.
3.5	685	35	720
10.0	710	50	475

13. Refer to Fig. 264*a* and *b*. The one opposite this problem shows a substitute for 264*b* when the armature has been started by giving it a turn counter-clockwise. Mark a direction of rotation which will result, using the same method as that found in the text at the place referred to.



14. A 10-hp. two-phase induction motor is to be operated direct from transformers which receive current from a 2200-volt line and deliver power to the motor at 440 volts. What capacity transformers shall be installed and what size fuses in secondary lines and in primary lines, allowing for a starting current having 200 per cent. of full-load value. (Induction motors of this size would have an efficiency of about 87 per cent. and a power factor at full load of about 86 per cent. Do not make transformers too small, since the voltage regulation would be poor.)

CHAPTER XV

OTHER ALTERNATING-CURRENT MACHINERY

176. Synchronous Converters.—Synchronous or rotary converters are machines used mainly to receive alternating current and transform it to direct current. In general appearance they are very similar to D.C. dynamos, having armature and field windings precisely like them. Fig. 267*a* shows by diagram the fundamental principle of construction. Fig. 267*b* is intended to show clearly what the diagram of Fig. 267*a* stands for. Taps from armature winding to collector rings as in Fig. 267*a* are shown in place. Suppose the dynamo to be revolving as a D.C. machine, and consider the e.m.f. between brushes *AA′* laid on slip-rings which are connected to opposite bars of the commutator. In the position shown the volts between brushes *MN* and slip-rings is the same, the voltage of the dynamo. When a quarter revolution is completed the difference of potential between slip-rings is nothing; when a half revolution is completed the voltage between slip-rings is again full dynamo voltage, but the reverse of what it

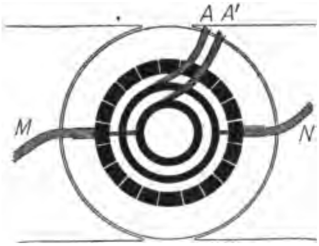


Fig. 267*a*.

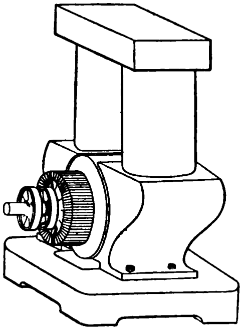


Fig. 267*b*.

was at first. It is clear then that from this D.C. armature we may draw through the slip-rings an alternating e.m.f. which has a maximum value the same as the direct e.m.f. on the commutator and having a frequency for this machine the same as the revolutions per second the armature is making.

But further, had intermediate taps been brought out to two other rings B and B', not only would an e.m.f. exactly the same as that between rings A and A' have been available, but it would have been different in phase by a quarter period. Alternating e.m.fs. could then be procured from four such slip-rings the same as from any two-phase generator.

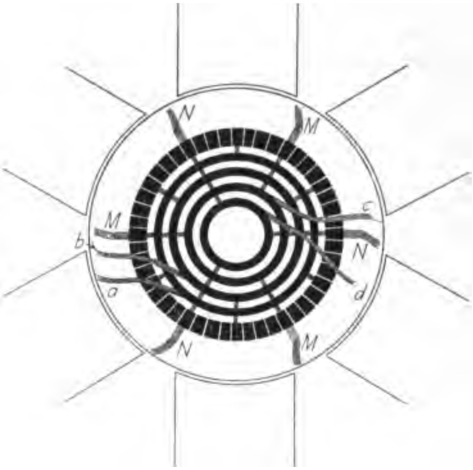


Fig. 268.

Now any two-phase generator will run as a two-phase synchronous motor. Hence if this machine, completed by the addition of two more rings with brushes on them were connected to a source of two-phase current at proper voltage, the machine when once started would run, and from the brushes rubbing on the commutator, D.C. can be derived both for the field windings and for an external circuit.

This armature in a two-pole field would have to make 1500 r.p.m. if connected to a 25-cycle supply, or 3600 r.p.m. on a 60-cycle supply. Hence synchronous converters are usually multipolar. Fig. 268 shows how connections are brought out for a six-pole machine to be connected to a two-phase supply. Examination of this will show at least that the three connections to each slip-ring are all right, since from the nature of the D.C. armature we know that all brushes *MMM* may be and are connected together for the positive machine terminal and so the bars on which they rest may all be connected to ring *C* (the one on which brush *c* rests), while in one revolution three cycles of A.C. would be generated, and so the speed as a synchronous motor for

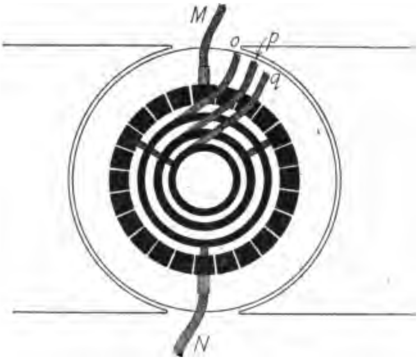


Fig. 269.

a 60-cycle circuit would be 1200 r.p.m. Fig. 269 shows a diagram for three-phase connections on a two-pole machine. There are three taps at equal intervals, each to its own ring. We can see that for the position of the armature shown in the figure the e.m.fs. from *o* to *p* and *o* to *q* are equal, while that from *p* to *q* is zero. The condition is that shown at line *xy* in Fig. 225 where e.m.fs. *B* and *C* are equal and opposite and *A* is nothing. The armature forms in fact a mesh-connected, three-phase piece of apparatus.

Fig. 270 shows a synchronous converter placed so both commutator and slip-rings can be seen. The collector rings at the right are well covered by the brushes resting on them; the commutator at the left is clearly built to carry a large current to the brushes there.

Looking again at either diagram it will be plain that since maximum alternating e.m.f. and maximum current (or nearly maximum) occur when the slip-rings have their connections direct to the commutator bars on which the brushes rest, most of the A.C. is directly transformed to the D.C. circuit and the whole of it never flows in the D.C. armature winding. A synchronous converter, therefore, has a greater capacity than the same machine used as a D.C. dynamo. The figures to show this are as follows:

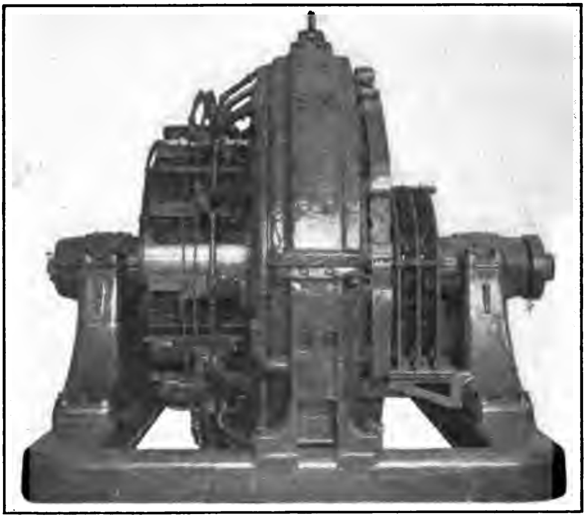


Fig. 270.

D.C. generator	100 kw.
As a two-phase converter	164 kw.
As a three-phase converter	134 kw.

The ratio of transformation in synchronous converters is fixed.

Two-phase converter: Direct e.m.f. = 1.4 × alternating e.m.f.
Three-phase converter: Direct e.m.f. = 1.63 × alternating e.m.f.

It is easy to see that the first of these must be true since the *maximum* alternating e.m.f. must necessarily be the same as the direct e.m.f. Varying the field strength of the machine will not change this ratio more than a small amount, for all that it accomplishes, as for any synchronous motor, is a change in the power factor of the supply and so in the *IR* drop in the armature winding.

177. Connections and Features of Construction.—The general plan of connecting a two-phase synchronous converter from A.C. lines to the D.C. system it serves is shown in Fig. 271, omitting all switching devices, instruments and starting apparatus. Rotary converters are often provided with a shunt field only. In such a case the field rheostat serves simply to control the power factor of the supply circuit and indirectly by it the exact e.m.f. delivered. As already explained for synchronous motors, the current can be made to lead the applied e.m.f. by strong field excitation. A series field can automatically correct the power factor.

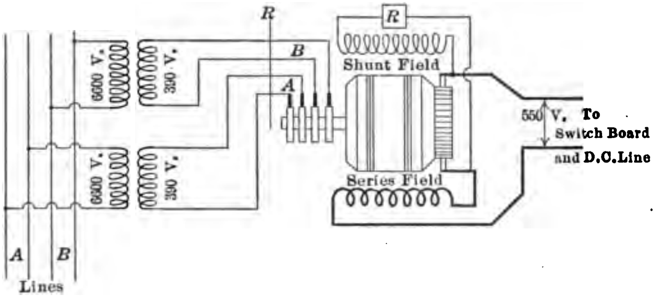


FIG. 271.

Many converters have commutating poles like those described in section 90. They keep the brushes from sparking and permit various features to be introduced into the design which make the machines rugged and safe in operation. Many converters have laminated field cores and poles, in the faces of which, in slots parallel with the armature slots, are copper bars joined at their ends to form low-resistance grids. These grids are built in for the purpose of preventing *hunting*. This is a phenomenon due primarily to the armature swinging alternately ahead of and then behind its proper synchronous position. The result is surges of current from the A.C. supply line which through armature reactions causes bad sparking at the brushes, pulsating e.m.f., and in bad cases results in the machine "flashing over" on the commutator or breaking from synchronism. Any of these troubles are serious enough. The last ones may result in the machine being seriously damaged. The grids in the pole faces, by induced secondary currents in them, damp out the disturbances.

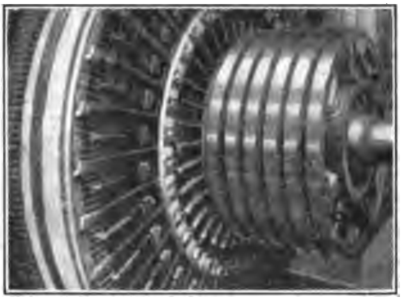


Fig. 272.

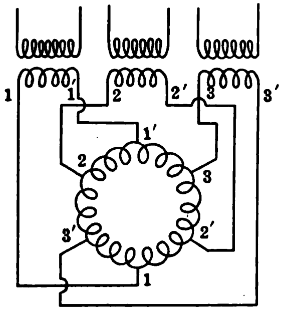


Fig. 273.

A great many rotary converters have an arrangement at the collector ring end like that shown in Fig. 272. These six rings show that it is a six-phase converter. Such machines are supplied from three-phase lines, one common method of connection being shown by Fig. 273. The converter is considered in the diagram as a two-pole machine, each numbered point corresponding to a brush on its own collector ring. The tap from each collector ring into the armature winding reaches a point corresponding to what Fig. 273 shows. The voltage-transforming ratio for a three-phase machine connected this way is the same as for a two-phase machine, but a greater current capacity is secured for a machine of the same size.

178. Starting Synchronous Converters.—Because they are synchronous A.C. motors they are not naturally self-starting. There are several possible methods in use for starting them.

A. *As D.C. Motors.*—When this method is used the field is excited from D.C. buses at the proper e.m.f.; and then using a proper resistance for starting, the armature is put on the line and brought to speed as any D.C. motor would be. It is then synchronized as is any alternator about to be put in parallel with others, and connected to the A.C. line.

B. *By an induction motor*, often mounted on the same shaft. The rotor has usually a squirrel-cage winding, but with high resistance and arranged so that with full-load slip the converter will come up to synchronous speed. The A.C. supply is connected to the motor. The converter starts up, picks up its field from its own residual magnetism, and when synchronized and at proper voltage is thrown on to the A.C. supply.

C. *As an Induction Motor.*—The winding as already explained is like that of a D.C. machine, but when polyphase currents are admitted a rotating magnetic field is produced exactly like that in any induction motor. The copper grids in the pole faces take the place of the squirrel-cage secondary winding and so when reduced voltage secured from special transformer taps is applied, the converter turns over and speeds up. At some speed near regular running speed, the switches are thrown over to give full voltage to the machine and it is ready for service. Two precautions must be taken, however. Before starting, the shunt field must be separated into several parts so that the high voltage generated in its many turns by the rotating field will not cause a failure of insulation. This is done by a field breakup switch. It is a multi-bladed knife switch mounted on the machine. There must be great care taken to be sure the D.C. side has "come up" with right brush polarity before putting the machine into service. It is as likely to come one way as the other. The same field breakup switch is used to correct the difficulty if things come wrong. It is made double-throw, and when put over to its other position the field gets reversed current and the armature slips ahead one pole thus correcting its own D.C. polarity. The switch is then thrown back to restore the field connections to normal operating condition.

In Fig. 274 is a diagram to show this method of starting when there are two low-voltage taps. The converter is on a three-phase line and receiving six-phase current to the machine by the plan of Fig. 273. The two switches S_1 and S_2 are mounted on the same panel, often close to the transformers and in starting are operated as follows:

1. To start with lowest voltage e_1 on the rotary, throw both switches to the left.
2. To transfer to a higher voltage e_2, leave S_2 where it is and throw S_1 to the right.
3. To throw full secondary voltage on the converter, throw S_2 to the right.
4. Open S_1 to be ready for next starting.

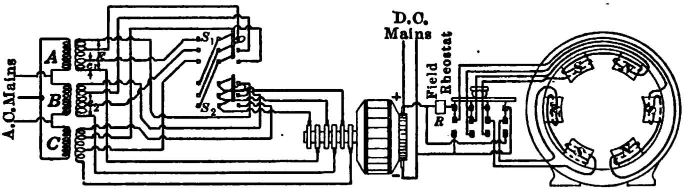


FIG. 274.

Since S_2 is in continuous use while the machine is operating, it is usually a larger capacity switch than S_1.

The diagram shows also a "breakup" switch connected for a six-pole field. It is shown closed in the proper position for running.

179. Special Uses of Synchronous Converters.—The same machines described in the last section can be used for a variety of purposes as follows:

1. *As Inverted Converters.*—The same machine is supplied with D.C. and from the collector rings A.C. is drawn. If this is done from a standard voltage direct-current line, transformers having a special transforming ratio must be used in order that there shall be proper A.C. voltage available for any commercial use. Inverted converters do not operate as synchronous motors but

as D.C. motors. When in operation there is always danger that they may "run away" as the result of a lagging current to the A.C. lines, causing such armature reaction as to seriously weaken the field. The machine speeds up then as would any D.C. motor with a weakened field. A speed-limiting device, arranged so that centrifugal force due to increased speed will operate a switch and trip the circuit-breaker on the D.C. supply, is commonly provided.

2. *As Double-current Generators.*—The machines may be operated by motive power so they are used at the same time as D.C. and A.C. generators.

3. *As synchronous motors,* the commutator being used only to supply current for field excitation.

180. Voltage Regulators.—Since the transforming ratio of synchronous converters is practically fixed, some plan must be used to keep the D.C. voltage exactly right on lighting service in spite of the effect of IR drop, peculiar A.C. wave-shape, lagging or leading current, etc. There may be contact voltage regulators as already described in section 136, the number of turns in the secondary being under control by a special moving dial switch device. But often the apparatus used is an induction voltage regulator. This regulator is precisely the same as an induction motor with wound rotor but with it adjustable to any desired position, and capable of being locked in any one. If the converter is two-phase, the regulator has its stator built like a two-phase induction motor, the windings being connected across their respective lines. The wound rotor has also a two-phase winding, for the same number of rotating poles (say six for definiteness) as provided by the stator, and these windings are connected in series in their respective phases between the transformers and the converter in region R of Fig. 271. Think now of the rotary field sweeping by the rotor windings, the rotor being locked in such a position that e.m.f. is generated in phase with supply line. This e.m.f. is bound to have the same frequency as the supply and will be adding its amount in series with that supplied by the transformers. If now by a hand lever or a small motor geared to the rotor shaft it is turned $\frac{1}{6}$ revolution, the e.m.f. will be just as large as before but displaced in phase so as to be the reverse of what it was before. Although still in series with the transformer supply, it now subtracts its amount. In this way and by intermediate steps, but without sliding contacts, the voltage given the converter can be controlled to any desired amount within the limits for which the apparatus was built.

181. D.C. Three-wire Generators.—One troublesome thing about the older three-wire D.C. systems is found in the fact that two dynamos must always run, one for each side of the system. Various plans have been devised to make this unnecessary, one of which will be here described. A machine built exactly like a synchronous converter, in this case tapped for two-phase connections, is driven by motive power as would be any D.C. dynamo to supply 220 volts between positive and negative brushes. To the slip-rings there are two coils, like auto-transformers, connected to each other at their middle turns. The point N then becomes a neutral to the D.C. three-wire system and is connected as shown. By a neutral point in any system is meant a point which is always midway in potential between the extremes of the system. It is a neutral to the four wires of the two-phase line from the collector rings, for a voltmeter connected from it to any one of them would read the same. It is also neutral to the D.C. lines. If the reader were to reproduce Fig. 268 so the armature could be placed in a number of positions and the difference in potential from N (Fig.

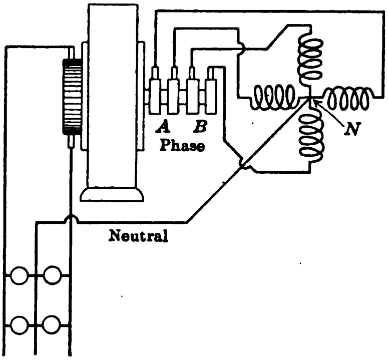


Fig. 275.

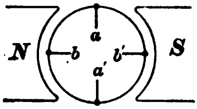
275) to each of the D. C. brushes were considered, it will turn out that it is always halfway in potential between them; that is, a voltmeter from it to either one would read the same. All the conditions necessary to the successful operation of a three-wire system are fulfilled. On unbalanced load the system does not maintain perfectly balanced voltage, but under usual working conditions it is good enough to be satisfactory.

It should be noted that if the coils were mounted within the armature to revolve with it, only one collector ring and brush for the *N*-connection need be used.

QUESTIONS AND PROBLEMS

1. In section 176 it is stated for Fig. 267 that when a quarter of a revolution is completed and taps *aa′* have reached the positions of *bb′* there is no voltage between the slip-rings connected to them. Explain why.

2. Draw a simple circular form like this, to represent an armature with taps for synchronous converter connections. State and explain the volts between taps *aa′* and *bb′* for the position shown and for two others, shown by diagrams made with the armature advanced 45° clockwise for the second and 45° farther for the third. On the D.C. commutator there are 200 volts between brushes, while the e.m.f. is generated evenly around the commutator.



3. In Fig. 269 a two-pole, three-phase synchronous converter is shown. There are 48 bars in the commutator; between adjacent bars there is an average of 5 volts all the way around. Draw three diagrams showing the armature in the position of Fig. 269 for the first, but using the form of diagram of the preceding problem. The second is to show the armature after turning 30° clockwise, and the third after turning 30° farther. Show for each, volts between taps to armature (or connections to collector rings), using values of commutator P.D. stated. The taps to collector rings are made on wires which enter commutator bars, and it is to be assumed that no coils are short-circuited by brushes on the commutator.

4. (*a*) Calculate the volts between collector rings of a two-phase synchronous converter if the D.C. volts are to be 500. (*b*) Calculate volts between collector rings if a two-phase machine is to supply 110 volts D.C. (*c*) Calculate again for a three-phase converter to supply 110 volts D.C.

5. A two-phase synchronous converter is delivering 230 kw. at 575 volts to a D.C. railway line. Current to operate it is drawn from a 10,000-volt, three-wire line. (*a*) If the combined efficiency of rotary and transformers is 90 per cent., how much direct current goes to load and how much A.C. over each line? Count the A.C. power factor at unity. (*b*) Recalculate if the power factor is 0.9.

6. (*a*) Make an outline diagram to show how to put in the armature taps for a four-pole, two-phase synchronous converter. There will be two for each collector ring. (*b*) Make one for a four-pole, three-phase converter.

7. In wiring a two-phase converter, might the lines from the secondary of the transformers be three-wire? When installing a two-phase converter what means might be taken to tell whether the four leads are properly connected at the switchboard before closing the main switch to put the machine into service?

8. A certain three-phase synchronous converter has eight poles. Looking over the taps to a certain collector ring I see they come out at intervals of 48 commutator bars; at 1, at 49, etc. How many taps are there to each ring? Give the location of taps for each of the other collector rings.

9. Using Fig. 275 as a basis, verify the fact that *N* is a neutral point by considering: (*a*) the position shown in the figure with the two collector rings at the left (the *A* phase) just now at maximum P.D., and those at the right (the *B* phase) just now at zero P.D.; (*b*) the armature moved around 45°. In either case if no load is on the system will any current flow in the coils connected at *N*?

10. A synchronous converter having eight poles and operating from a 25-cycle circuit is started by an induction motor mounted on its shaft. If the induction motor has six revolving poles, what per cent. slip will it have to just bring the converter up to synchronous speed, ready to throw on the line?

CHAPTER XVI

STORAGE BATTERIES

182. First Principles.—All batteries are made by immersing two conductors, called electrodes, in a conducting solution. This conducting solution is called the electrolyte. If the conductors thus immersed are different, an e.m.f. is found to exist between them. This may be used to send a current. The direction of e.m.f. and of flow of current when the circuit is completed is indicated in Fig. 276 for some combination of electrodes and electrolytes. The electrode out of which current flows to the external circuit is called the positive. The other electrode is the negative. A battery may be a single cell, as just described, or a number of cells suitably grouped.

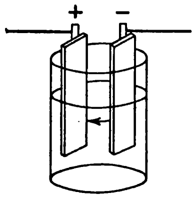


FIG. 276.

When current is flowing through a cell, a chemical action goes on in the electrolyte. Molecules[1] of the chemical which is in solution dissociate, each into two parts, one of which goes with the current and the other against the current. At the electrodes they are liberated, and there secondary chemical actions occur. Usually the electrodes are acted on chemically, new products forming there. As the electrolyte is gradually changed in character and the electrodes also, it is certain that the e.m.f. (determined by their character) will change also as the cell is used.

When current is sent through a circuit by a battery, watts of electric power are being used and watt-hours of energy spent. The energy is derived from the chemical energy of the cell. The presence of an e.m.f. indicates the presence of chemical energy which can be drawn on by completing an electric circuit. Usually a test of the chemical condition of a cell will tell at once whether an e.m.f. may be expected or electrical energy derived from it.

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[1] A molecule is the smallest quantity of a given material which can exist as such.

183. Storage Battery Defined.—A storage battery is a battery so made up that when its chemical energy is exhausted, it is possible by sending a reversed electric current through it to restore electrolyte and electrodes to their original condition and so to store in the battery once more the chemical energy originally there. This process is called charging the battery. The process of taking energy by allowing its e.m.f. to send current is discharging. Storage batteries are often called secondary cells with this thought in mind: electrical energy is put into them and stored as chemical energy, so that as a secondary action electrical energy can be derived from them.

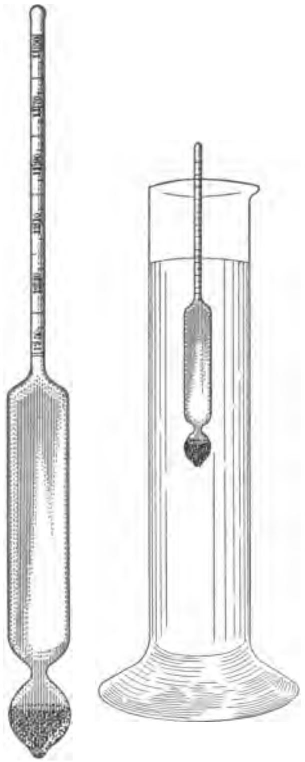

Fig. 277.—The right-hand view shows the hydrometer in use.

Long experience has shown that to be successful a storage battery must be one in which the final chemical action resulting from charging and discharging, produces definite effects on the electrodes only. The electrolyte may alter in the amount of the chemical found there in solution, but its character does not change.

184. Specific Gravity.—If a chemical is put into water and dissolves or mingles with it, the weight per cubic inch of the liquid has changed. 27.7 cu. in. of water weigh 1 lb. The same amount of sulphuric acid (often called oil of vitriol) weighs 1.84 lb. If now equal quantities of water and acid are mixed, the weight of 27.7 cu. in. of the mixture will be 1.42 lb. By the specific gravity of a liquid is meant the weight of a given amount compared with the same amount of distilled[1] water. Thus the specific gravity (later abbreviated to s.g.) of water is 1; of sulphuric acid is 1.84. In a storage battery the s.g. of the solution changes so that it is greater when the battery is charged and less when discharged, as the result of the chemical action which has occurred; but the solution of sulphuric acid and water experiences no change except that of s.g., no matter what chemical actions go on at the electrodes.

To measure s.g. a hydrometer is used. Fig. 277 shows one form. This instrument when immersed in a liquid sinks to a depth determined by the s.g. of the liquid. A reading on the stem at the level of the liquid surface shows the s.g. In a liquid of high s.g. the bulb sinks only a short distance; in one of low s.g. it settles deeper into the liquid.

It is common to call the s.g. of water 1000 rather than 1.000, and so 1200 s.g. acid would be that which is 20 per cent. heavier than water. If one liquid had a s.g. of 1220, and another a s.g. of 1250, the s.g. of these two would be said to differ by 30 points.

To secure acid at proper s.g. for battery use, the mixture might be made as follows: The proportions are given by volume. Acid must always be slowly poured into water, preferably in an earthenware vessel, and must be cool before s.g. readings are made.

1300 s.g.	1 part acid to	2.47 parts water
1250 s.g.	1 part acid to	3.22 parts water
1220 s.g.	1 part acid to	3.84 parts water
1200 s.g.	1 part acid to	4.33 parts water

185. Storage-battery Resistance and Capacity.—The resistance of a storage battery has an important relation to its practical use. For practical purposes it is usually important that the battery supply current at constant potential. The variation of its e.m.f. with condition of charge makes things bad enough; but under varying amount of current flow the terminal volts will vary still more. The smaller the internal resistance, within limits, the more desirable the cell.

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[1] Distilled water is water purified from anything dissolved in it by boiling and condensing the steam so formed in the process. The condensed steam is the distilled water.

Now the resistance of any liquid is relatively high (see section 7). To have low resistance a cell must be so built that the area for the passage of current through the electrolyte must be large and the distance for it to go from negative to positive electrode through the solution must be short. Storage batteries are constructed with this in view. The electrodes are set very close together and to get large area each one is made up of a number of plates. Thus for example, five positive plates may be joined together for the positive electrode, and six negative plates for the negative electrode. They can be then intermeshed. Fig. 278 shows two sets of plates or groups partly assembled to form the element referred to. When the two sets are completely intermeshed special insulating spacers must be installed to prevent positives touching negatives. (See Fig. 279 for plates assembled with spaces to form an element.) In the arrangement of 278 the current would have 10 paths to flow in, making the resistance of the cell one-tenth as much as though only one positive and two negative plates of the same size were used. The resistance of the electrolyte increases very much with a reduction of temperature, and also with changes in its s.g. The following tables illustrate these facts. Resistance stated is in ohms for a column of sulphuric acid and water 1 sq. in. in cross-section and 1 in. long.

S.g. at 20°C.	Resistance
1050	0.43
1100	0.31
1150	0.25
1200	0.22
1250	0.20
1300	0.22
1350	0.29

Temp. °C.	Resistance for 1200 s.g. acid
0	0.52
5	0.42
10	0.34
15	0.27
20	0.22
25	0.18
30	0.15

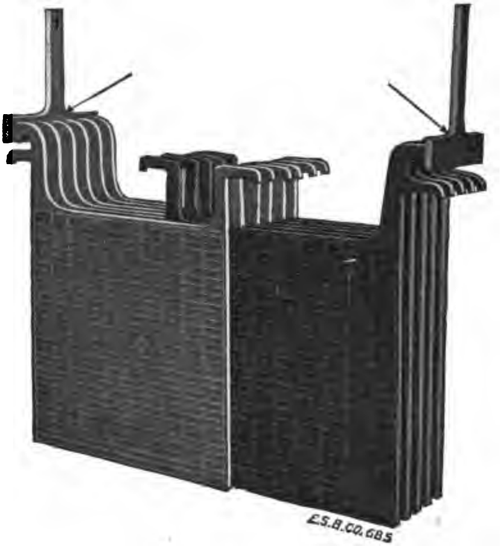

Fig. 278.

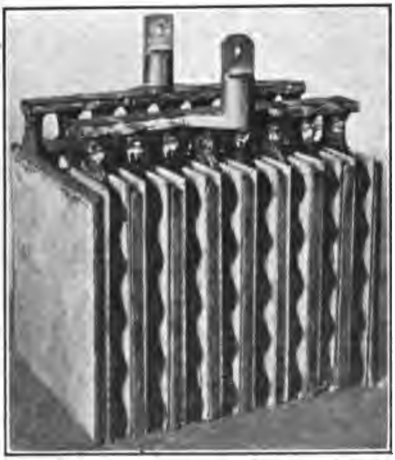

Fig. 279.

At about 20°C., below zero (— 4°F.) there is a chance that battery acid may freeze if the s.g. is low. In such case the resistance gets very high.

The amount of energy which can be taken from a battery depends on the amount of chemical action which can go on in it, on the amount of chemical material in the electrodes, and the amount of acid in the electrolyte which can take part in the chemical reactions. The chemical material in the electrodes available for use is known as the *active material*. The energy taken from a cell is the number of watt-hours it delivers; that is the volts at the terminals multiplied by the current it is delivering, and that product by the number of hours it can be taken. *The capacity of a cell* is this number of watt-hours. Capacity is even more usually stated in ampere-hours; that is the product of the steady current flowing in discharge by the hours it can be continued, or an equivalent. The relative capacity of cells of the same kind can be known by observing the amount of active material in any of them.

186. Modern Types.—Two types of storage battery are in successful use to-day. One of these is known as the lead-sulphuric-acid type, and the other as the nickel-iron-alkali type. The first has been in use for many years and is well known; the e.m.f. of a cell of this type is counted at 2 volts. The second is a newer form; the e.m.f. per cell is 1.2 volts. It is much easier to describe each by using examples from their makers than to generalize, and this is done in succeeding sections.

187. Lead-sulphuric-acid Cell.—There are two ways of making such cells; both regularly employed. Each will be briefly described.

If two lead plates are immersed as electrodes in a solution of sulphuric acid and water, having a s.g. of about 1200, and current is passed through this cell, for a time in one direction and then the other, the positive plate takes on a seal-brown color (slightly purplish) which reveals the presence of a material which a chemist would tell us is peroxide of lead; while the negative plate is a bright grayish-lead color in porous formation, which is spongy lead. These chemical products, the active material of the cell, are formed directly from the lead of the plates. The method used is called the Plante process. In practice the plates are so formed that the active material does not fall off, but becomes wedged into place. It is then in proper electrical relation to the electrode where it must be to take part in the chemical action in the cell. Fig. 280 shows a construction used by the Electric Storage Battery Company (later abbreviated to E. S. B. Co.). The plate proper (of which only part is shown) is a casting of lead with enough antimony in it to make a stiff plate and one on which the chemical action will be very slight. The holes in the plate increase in diameter from the middle of the plate toward both sides. Into each hole there is pushed a "button" made of lead ribbon corrugated on one side as shown in some detail in the cut. The openings through the "button" afford lodgment for the active material formed from the ribbon itself. These plates, known as Manchester positives, are used in one type of battery. Fig. 281 shows a group ready to be used in a cell.

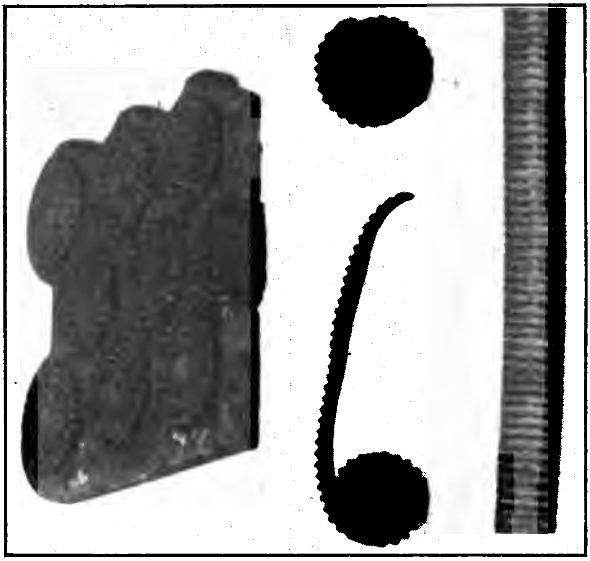

Fig. 280.

If a lead framework is formed into which certain lead oxides can be pasted, storage battery plates can be formed by the passage of current as for charging. This method is known as the Faure or pasted plate process. Fig. 282 shows one form of such construction which is used by the E. S. B. Co. (after forming) as the negative plate with the positive just described. A framework or grid having 25 windows through it, has had these filled with the proper lead oxide which is covered in by thin lead sheets perforated opposite the active material. These perforations give the darkened appearance at the window areas in the figure. The plate is a "box negative." Fig. 279 shows the positive of Fig. 281 and the negative of 282 assembled.

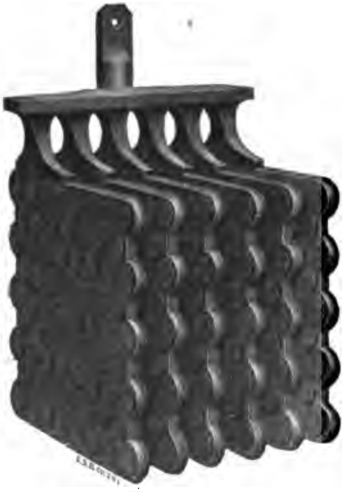

Fig. 281.

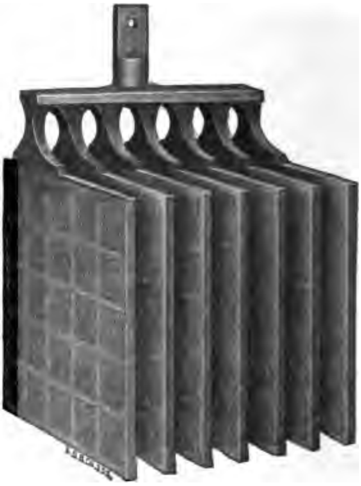

Fig. 282.

Fig. 283 shows a grid which is used for making the plates of a cell known by the trade name of Exide. Into such grids red lead is pasted if a positive plate is to be made, while into others litharge would be pasted to make negatives. The pasted material is made into a dough-like mass with acid and water and then pasted in. When the contents of the grids have hardened they are immersed in 1200 s.g. acid and a charging current turned on. The resulting chemical action changes the red lead to peroxide and the litharge to spongy lead. After the plates are formed they are ready to be used in storage-battery work.

Details regarding the construction of these and of cells made by other manufacturers can be secured from catalogues and instruction books. Firms making lead cells can be learned from the advertising pages of the technical journals.

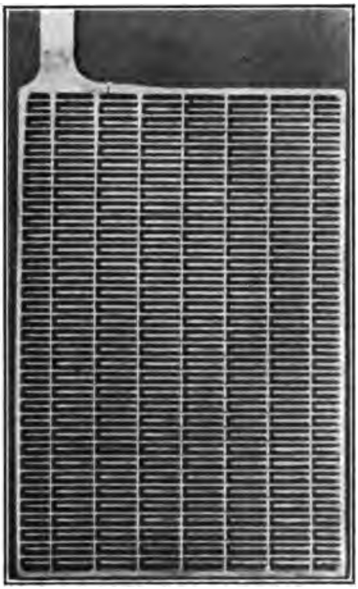

Fig. 283.

Lead-sulphuric-acid cells are assembled in glass jars (see Fig. 284 for a complete cell) if they are not to be moved around, or in lead-lined tanks if the cells are large. Vehicle cells are commonly in hard-rubber jars as shown in Fig. 285 which is cut away to show the internal arrangement of an "Ironclad-Exide" cell. This cell has the negatives made as in Fig. 283; the positives have grids of a series of vertical lead rods joined at top and bottom, around each of which is a horizontally laminated hard-rubber tube between which and the grid rod, the peroxide has been formed. A vent plug at the top of a sealed-in cover is provided so the acid will not slop out; but gas evolved may be liberated and the electrolyte examined.

188. E.m.f. of Lead Cells.—The e.m.f. or open-circuit voltage of a lead cell is commonly stated as being 2.00 volts. Immediately after charge or discharge the e.m.f. is slightly affected, but after the cell has stood for any appreciable time the e.m.f. will settle down to something between 2.00 and 2.05 volts. The density of the electrolyte is the chief factor in determining the e.m.f. If it is 2.05 volts at 1210 s.g. it may be 2.00 volts at 1170 s.g., the battery being in the same condition of charge. It will be clear from this that the e.m.f. or open-circuit voltage of a cell is no indication of its state of charge or discharge. When fully charged and with normal charging current flowing, the P.D. may lie anywhere

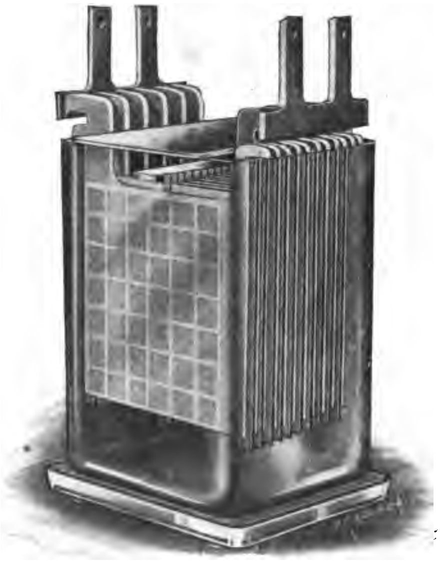

Fig. 284.

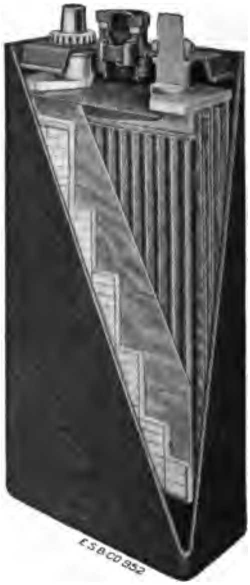

Fig. 285.

between 2.4 and 2.8 volts. While the e.m.f. will then be higher than the 2.05 mentioned above, immediately after the charging current is taken off it will rapidly settle to approximately 2.05 volts. The P.D. reached at charge is influenced by the temperature of the cell, its type and its age.

If a fixed current is taken from a cell which will discharge it in 8 hr. the terminal P.D. will be about 1.97 dropping gradually to 1.90 in about 6 hr. After this it drops more quickly to 1.8 and at last rapidly to 1.75 when the discharge should be stopped. If the discharge current is cut off, the e.m.f. rises almost at once to a figure nearly as at the beginning of discharge; for the electrolyte, depleted of acid in the pores of the plates by the chemical action which has been going on, immediately receives a new supply from the body of the liquid.

In order to judge the condition of a battery by voltmeter readings, they must be taken with current on. When batteries are in good condition and with "normal" current on, the drop on the cell due to its resistance is about 0.03 volt.

189. Rating and Capacity of Lead Cells.—As already stated, the capacity of a storage cell depends on the amount of active material and acid available. A battery is not rated in terms of all the energy which can be taken from it, however, for experience shows that it is bad to discharge after the P.D. with normal discharge current has reached 1.75. Manufacturers rate their cells in terms of a normal current which will discharge them in a certain stated time. For stationary cells this might be 8 hr.; for vehicle cells 4 hr. Thus

Cell	Ampere-hours capacity	Normal current	Time of charge, hours	Use of cell
F. Chloride....	320	40	8	Stationary
M. V. Exide...	280	70	4	Vehicle

Stationary cells of the heavier types will have the normal current somewhere near 0.04 amp. per square inch of positive, having a capacity of 4 amp.-hr. per pound of element (positives and negatives); vehicle cells would show figures twice as large as these.

When cells are put on steady discharge at other than the normal rate, the capacity alters as shown by the following table.

Hours of discharge	Per cent. of capacity
8	100.0
5	87.5
3	75.0
1	50.0

The reason for this condition of affairs is that the acid within the pores of the plates is used up first (its s.g. runs down) and there is no time to restore this acid by diffusion from other parts of the liquid since the discharge is continuing. If, however, the discharge is intermittent and at reasonable intervals, even though very high discharge rates are used, practically the whole capacity of the cell is available.

190. Charging and Discharging.—When a battery is in use it is important to be able to tell its condition of charge at any time. Voltmeter readings are of some help if taken with normal current flowing. Ampere-hour meters are often installed in the battery circuit to give direct reading of the ampere-hours which have been taken out or which are being put in. The best indicator is found, however, in the s.g. of the electrolyte. The strength of the electrolyte used in the cell determines its s.g. when fully charged. It might be 1200, 1275 or some intermediate value. The drop in s.g. for a full discharge cannot be given since the relative amount of electrolyte and number of plates in different cells determines it. One manufacturer has types and sizes of cells for stationary service with s.g. drop on discharge varying from 12 to 42 points. A vehicle cell on full discharge will show a drop in s.g. of 100 to 150 points due to the restricted amount of electrolyte used. In a given cell the drop in s.g. of electrolyte on discharge is approximately in direct proportion to the ampere-hours discharged. Thus if in a certain cell the drop is 40 points when 50 amp.-hr. are taken out, it will drop 80 points when 100 amp.-hr. are taken out without regard to the rate of discharge. A given cell varies in s.g. of electrolyte over a fixed range when properly charged and discharged. The only things which cause a departure from uniformity are the evaporation of water from the electrolyte and changes in its temperature.

If a constant current is flowing throughout discharge the s.g. drops uniformly; on charge it rises uniformly. The best test of a cell being fully charged is to find that the s.g. of the electrolyte has ceased to rise when the charging current has been continued at a proper rate for an hour.

There is no special discharge current for a given cell. Any discharge current may be used safely if the cell is not discharged too low. In this connection it may be noted that if the lowest P.D. permitted on normal current at full discharge is 1.75 volts, on double the normal discharge rate at the end of discharge the terminal P.D. would be 1.72 volts, for with the same e.m.f. double the normal drop in the internal resistance of the cell must occur. At the end of charge no fixed terminal P.D. is to be found. With normal charging current the terminal P.D. may rise at the end of charge to 2.45 volts or it may reach a figure as high as 2.8.

In charging either one of two methods is used; constant-current, or constant-potential is employed. These methods are discussed later in sections 195 and 196. In either case for lead cells the plan is to so charge that gasing is avoided. Modern cells are often marked with two charging rates, the "normal" and the "finishing" rate. The second is used to finish the charge after gasing has begun.

The efficiency of a lead-sulphuric-acid battery should be 70–75 per cent. if the ratio of watt-hours at discharge to watt-hours at charge is considered. The ampere-hour efficiency should be near 90 per cent. If charged at constant normal current for 9 hr. after a discharge at normal current of 8 hr., the ampere-hour efficiency would be $\frac{8}{9} \times 100$ or nearly 90 per cent.

191. Care of Lead-sulphuric-acid Cells.—In caring for storage batteries the following are most important:

(*a*) Keep the level of electrolyte ½ in. above the tops of the plates filling with pure water only to make up for evaporation. Sometimes distilled water is necessary.

(*b*) At fixed intervals of a couple of weeks give the battery a slow charge (at the finishing rate) until the s.g. of the electrolyte does not rise higher in an hour's time. This is more important for vehicle than for stationary cells.

(*c*) Keep the s.g. of the electrolyte at its proper figure. Never add concentrated acid, and do not add electrolyte without first consulting the instruction book of the manufacturer of the battery. Low s.g. commonly indicates insufficient charge.

(*d*) Do not let the cells gas unnecessarily; gas them only as instructed by the manufacturer. By gasing is meant that evolution of gas resulting from chemical action on the passage of current which gives the electrolyte the appearance of boiling. Acid is wasted, and acid spray projected into the room where the charging is in progress if unnecessary gasing is permitted, while excessive amount of active material is being loosened from the plates and so lost to usefulness.

(*e*) Never allow the temperature of the cells to rise above 110°F. Their life is reduced and permanent harm done them if this is not observed. A reduction in charging current will reduce the temperature rise.

Certain other matters might be included here, but a complete set of instructions as supplied by a manufacturer of batteries is necessary if best results are to be obtained.

(*f*) *Loss of Active Material.*—As charges and discharges succeed one another, a certain amount of disintegration of active material occurs and it falls in finely divided particles to the bottom of the cell. A sludge or mud is thus formed of increasing thickness. It must never reach the bottom of the plates; for if it does, no charge can be put into or held in the cell, as the plates are short-circuited.

(*g*) *Ventilation.*—There is always a certain amount of gas set free in charging. This is an explosive mixture if allowed to accumulate. Hence ventilate charging rooms. Never bring an exposed flame near the battery when it is gasing or shortly afterward.

(*h*) *Sulphating.*—When a cell is too far discharged, or when it is allowed to stand without being fully charged, a white chemical forms on the positive plate which is an insulator and seals some active material from its proper chemical action. Wrong s.g. of electrolyte may also cause it. An overcharge at intervals helps to prevent it forming. Prolonged overcharging may drive it off; usually accompanied by loss of active material.

(*i*) *Buckling.*—When chemical actions in the active material of the electrode goes on irregularly or so rapidly that acid is exhausted locally, the plates may be forced out of shape by the mechanical pressure produced in them. This is particularly true in the positives, where on discharge the peroxide changes to sulphate which takes up more room. By taking a cell apart and working carefully, buckled plates can sometimes be straightened; but at the cost of detached or lost active material.

(*j*) *Impurities.*—When the electrolyte contains other acids or shows the presence of small amounts of any metals but lead, the battery cannot be kept charged and complex chemical actions go on which will ruin the cells. Impurities may be introduced by using ordinary faucet or well water to fill cells, or by allowing metal particles to get into the cells. The sulphuric acid used must be that made from sulphur. Have the manufacturer approve the water used for replacing evaporation.

192. Nickel-iron-alkali Cell.—This battery has the positive plate of nickel-plated steel containing nickel hydrate for the active material. The negative plate is also of nickel-plated steel containing iron oxide as the active material. The electrolyte is caustic potash in water with (it is said) a slight amount of lithia. Its specific gravity is 1200. In charging and discharging, the nickel hydrate and the iron oxide both change chemically while no change occurs in the caustic potash solution. The e.m.f. is roughly stated at 1.2 volts.

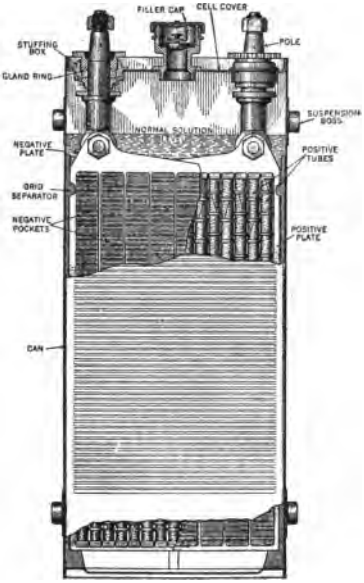

Fig. 286.

Fig. 286 shows how this cell is put together by its makers, the Edison Storage Battery Company. A large amount of special machinery is used in preparing the material for and assembling the battery. The positive iron plate has a series of windows in it into each of which is placed a tube of thin nickel-plated perforated steel within which under heavy pressure nickel hydrate and nickel flake are rammed into place. These tubes in position are shown in the figure. The negative plate has also a series of windows cut in it, into which are placed negative perforated pockets or boxes into each of which black iron oxide has been put under heavy pressure. Plates are assembled in groups as already described for lead cells, the positives being intermeshed with the negatives but separated from them by insulators. The assembled group or element is then surrounded by thin sheets of hard rubber and the whole slipped into an iron case or container. This has the sheet-iron top welded on, the terminals coming up through insulating bushings which fit them, making air-tight joints. There is also in the lid a filler opening which is kept nearly air-tight also, except when the solution is to be looked after or accumulated gas pressure from within opens a safety valve below the filler cap. The caustic potash solution must be kept from the air; for if not, chemical action occurs and the solution becomes worthless.

193. Rating, Performance, Etc.—The nickel-iron-alkali cell is usually rated on a 5-hr. discharge. Thus one having a capacity of 150 amp.-hr. is said to have a normal charge and discharge rate of 30 amp. When fully charged, with normal charging current on, the P.D. on a cell is 1.8 volts or more. On discharge with normal current on the terminal voltage is about 1.42 at the beginning, falling quickly to 1.3 and then gradually until the capacity is nearly exhausted to 1.1. After that it may rapidly fall to 0.9 at the end of discharge. The makers state that one of these cells may be used at any current rate; be completely discharged and allowed to stand that way without harm; does not sulphate. Further, the plates do not buckle because they are made of steel. Rather high internal resistance is a disadvantage. The cells as delivered to customers are completely sealed up, the lid of the steel container being welded on. The only care these cells need is to keep the level of the electrolyte above the plates and to have it renewed after a period of perhaps 2 years. The cells must not be operated at high temperatures (above 115°F.). They give off no noxious fumes, but the gases evolved from the cells are explosive as are those from lead cells.

194. Uses of Storage Batteries.—Almost invariably in order to secure the e.m.f. required for practical service a number of cells are connected in series. It will be obvious that 10 lead cells, connected in series with their e.m.fs. all directed the same way will supply an average of 20 volts to apparatus they are to serve with current. A diagram for such an arrangement would be made as in Fig. 287.

The uses mentioned here are chosen with the idea of connecting storage battery use with the D.C. circuits and apparatus mentioned in the earlier chapters.

1. On constant-potential D.C. systems they are used to supplement the dynamo when there is a heavy demand for current by operating in parallel; to "float" on the line neither giving nor receiving current and acting simply as a stand-by; to supply current when the dynamo is not running. In Fig. 288 a simple diagram for this is shown. By means of the end cell switch, at the left end of the diagram, the right number of cells can be selected to supply proper line voltage. If a battery e.m.f. greater than line voltage is used, the battery supplies current to the system. If the battery e.m.f. is less than line voltage current flows in from the line to charge the battery. Such an arrangement is used with commercial systems of 110, 220, 550 volts.

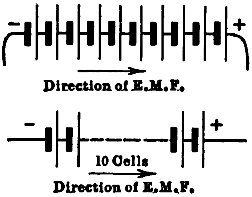

FIG. 287.

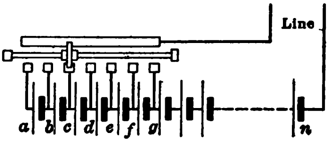

FIG. 288.

2. They are used as a main supply of current to house-lighting systems, a dynamo being used to charge the battery at convenient times, and to supplement the battery when there is a heavy demand for current. Such systems usually operate at 110 or 32 volts. Fig. 289 shows such a system. It shows 16 lead cells at the left and three counter e.m.f. cells next to them at the right-hand end of the row. Counter e.m.f. cells are storage-battery cells in which plates are used containing no active material. They replace a rheostat in series with a battery and give a drop of

about 2.5 volts each irrespective of the current through them. Their use may be illustrated in the case shown thus.

The 16 cells when charging may have a P.D. of 2.3 × 16 = 36.8 volts. If the lamp circuit is closed while the cells are charging, the circuit connections being such that the counter e.m.f. cells are in series with the line to the lamps, there would be on the lighting line 36.8 − 2.5 × 3 = 29.3 volts.

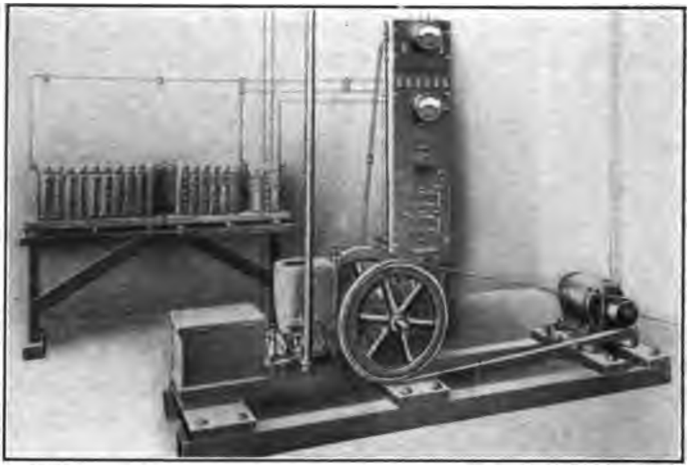

Fig. 289.

The number of cells usually installed varies with the minimum voltage to which the cells are allowed to go. Under ordinary conditions we might find:

Volts of system	Type cell	Number used
110	Nickel-iron	94
110	Lead	62
30	Nickel-iron	24
32	Lead	16

3. They are used for operating motor-driven vehicles. In this case 34 to 44 lead cells would be used, which are connected by a controller in combinations of series and parallel arrangement, so

that at the motor, requirements of speed and current for heavy pulling are best met.

4. They are used on gasoline automobiles to furnish current in connection with a small dynamo for ignition, lighting, and by operating the dynamo as a motor to start the engine. For this 6 volts is common, three cells of lead battery or five cells of nickel-iron battery being used.

5. On steam railroad cars to supply current to lights, they are used directly, simply discharging while in service; or more commonly to supply current to lights while the car is at rest or moving slowly, but in conjunction with a dynamo driven from the car axle when proper speed has been attained. The dynamo then supplies lights and charges the battery—64 or 32 volts are used for this purpose.

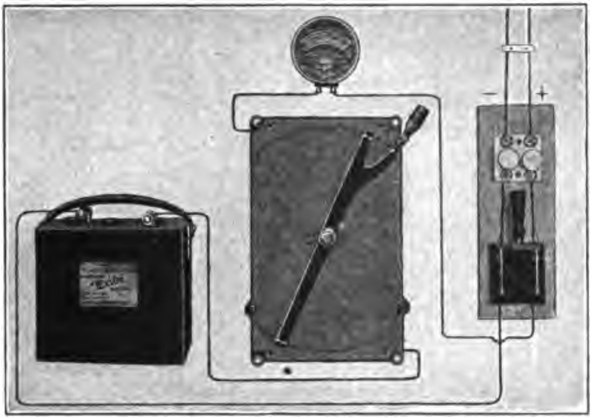

Fig. 290.

195. Constant-current Charging from Constant-potential Circuit.—Connections for charging batteries from a constant-potential D.C. circuit are shown in Figs. 290 and 291. The correct direction for current flow may be ascertained by the use of a polarity indicator (see section 81) or by using a compass needle (see section 22) or by ammeter and voltmeter readings interpreted by the + mark on the binding posts. The cells are connected, the current is set to normal value by adjusting the resistance in series (see Fig. 290) and the charging is in progress. The end of charge may be told by noting that without change in the amount of charging current the terminal volts on each cell or on the set have become fixed for 20 min. or more. The value is likely to be about 2.5 for a lead cell and 1.8 for a nickel-iron cell. During charge the resistance must be diminished to keep charging current constant. When a considerable number of cells are in series, or if they are of moderate or large capacity, the charging is to be ended after the cells begin gasing at normal rate by dropping the current to about one-third of the normal rate and finishing at that. In such case the final voltmeter reading may not be so high as just stated. For constant-current charging of lead cells when the amount of current which can be used is not limited, the E. S. B. Co. recommends the use of the following formula:

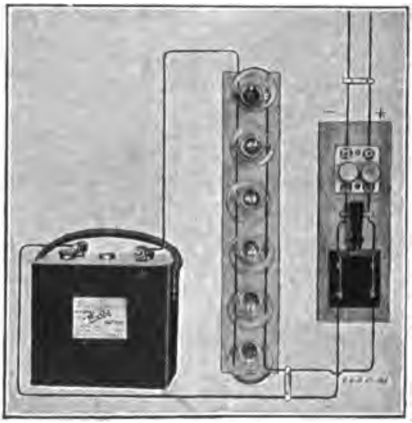

Fig. 291.

$$\text{Charging current in amperes} = \frac{\text{ampere-hours already discharged}}{1 + \text{hours available for charging}}.$$

Lamps are often used for resistance, and an approximate idea of the amount of current flowing can be obtained by noticing the appearance of the filaments and estimating the current in each. The arrangement is shown in Fig. 291. The amount of charging current is regulated by varying the number of lamps in use. This plan is not satisfactory unless the voltage of the charging circuit is considerably higher than that of the battery being charged. In such case the efficiency is very low.

196. Constant-potential Charging.—An economical way to charge batteries is to put them directly on a constant-potential line and let them receive the current which may flow. This current at the beginning of charge may be several times normal current; even equal to the ampere-hours which have been taken out of the battery on discharge. As the cells charge the current flow tapers off. An example will make this clear.

A set of 44 lead vehicle cells are in series for service. They have a capacity of 160 amp.-hr. each and an internal resistance of 0.002 ohm each. 40 amp. is their normal 4-hr. charge and discharge rate. At the end of discharge on normal current, they have 1.85 volts P.D. each, and they are immediately put on a 100-volt line for charging.

The drop in each cell due to the current is $40 \times 0.002 = 0.08$ volt. The e.m.f. of each is therefore 1.93 volts.

$$\text{Charging current} = \frac{100 - 1.93 \times 44}{0.002 \times 44} = 171.3 \text{ amp.}$$

As the charge proceeds the battery e.m.f. rises. When it has reached 2.05 volts per cell we have

$$\text{Charging current} = \frac{100 - 2.05 \times 44}{0.002 \times 44} = 111.4 \text{ amp.}$$

In this way the current falls until it reaches a fixed minimum when the batteries have their highest e.m.f.

In this method of charging there must be no more than 2.3 volts of charging e.m.f. per cell used; for with too large a current the temperature of the cells is too great. It is a quick and an economical method since no rheostat is in use.

197. Charging from D.C. Shunt Dynamo.—A set of batteries may be charged from a D.C. shunt dynamo driven as shown in Fig. 289 or by an A.C. motor. If the dynamo has more e.m.f. than the battery, the battery will charge.

Thus suppose the battery is made up of 16 lead cells now at 2 volts e.m.f. each, and that each has a resistance of 0.03 ohm while the dynamo is generating 34 volts and has a resistance of 0.5 ohm. A charging current would flow amounting to 2.04 amp.

$$\frac{34 - 16 \times 2}{16 \times 0.03 + 0.5} = 2.04 \text{ amp.}$$

Should the dynamo drop its e.m.f. to that of the batteries they would stop charging. Should it drop still lower the dynamo would be run as a motor, by current from the batteries, in the same direction as it has been running as a dynamo. It is customary to put into circuit an automatic magnetic circuit-breaker which will open the circuit when the charging current drops too low. One is shown at the bottom of the switchboard in Fig. 289. During charge the proper amount of charging current is maintained by adjusting the field current of the dynamo.

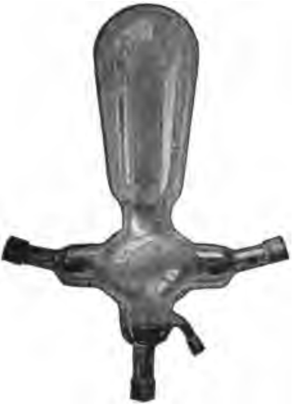

FIG. 292.

198. Charging by Mercury Arc Rectifier.—A mercury arc rectifier is shown in Fig. 292. It furnishes a means of rectifying A.C. and may therefore be used for battery charging. The tube has four terminals which pass through the glass, terminating in graphite electrodes. Over each of the two lower ones there is a pool of mercury. The tube is exhausted of air, and contains only mercury vapor. If e.m.f. is applied between any electrodes the resistance is too great for current to pass. The method of starting current through it and its plan of operation are described in connection with the diagram marked Fig. 293.

If the tube connected as shown is tilted so the mercury bridges the space between electrodes *A* and *B*, an arc forms as the tube is put back into its vertical working position. If at that instant *D* is positive, the arc will shift and pass from *D* to *A*, a charging current passing down through the batteries. At the time when the e.m.f. reaches zero, the arc would cease were it not for coils *SS* which with charging current have an e.m.f. generated in them to make the D.C. persist (see section 106). The zero of e.m.f. having passed and *C* becoming positive, the arc passes from *C* to *A* and the direct current down through the batteries continues. If the arc ceases for any cause, the whole starting operation must be begun again, for high resistance at the electrode *A* must be kept broken down by the presence of an arc or no action is possible. About 15 volts is lost in the arc in the tube. To get the right e.m.f. to supply the battery with proper current, the auto-transformer from which current is derived is tapped at the proper point by the aid of a dial switch as shown in the diagram. When in operation the mercury pool is violently agitated by the boiling of the mercury. It constantly condenses in the upper part of the tube.

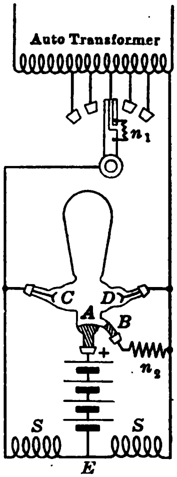

Fig. 293.

199. Charging by Vibrating Contact Rectifier.—This apparatus operates by using the magnetic effect of an alternating current to operate a vibrating armature to swing synchronously with it, opening and connecting a circuit in such way that when the alternating e.m.f. is properly directed to charge the battery it is connected to it. The principle of such an apparatus is shown in Fig. 294. Here an electromagnet has a permanent magnet as an armature with poles as marked, supported on a spring strip solidly secured at *p*. When it moves down a contact closes at *C*; when it moves up this opens.

Suppose now current from the A.C. line flows in at *a*; the magnet has current in its coils which sends flux out opposite the *N* pole of the magnet armature. The armature is repelled, contact *c* closes and a charging current flows through the battery. When current in the A.C. line reverses the flux in the magnet reverses and the armature is attracted, breaking the contact *C* so that no current is sent through the battery in the wrong direction. When an alternating current is reversing every $\frac{1}{120}$ sec., if this apparatus works, the natural rate of vibration of the armature must be practically the same as the rate of reversal of the A.C. It must work synchronously. The permanent magnet as an armature is not practical; it would soon have the magnetism shaken out of it. In rectifiers made by the companies which supply them, various ingenious adaptations of the principle are made. These rectifiers are to be used only when currents of not over 6 amp. are to be used in charging low-voltage batteries. Some skill is required in making exact adjustments, especially to avoid sparking at the contact and to have satisfactory operation on circuits which do not supply a constant frequency.

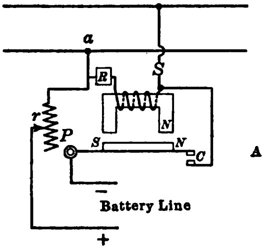

FIG. 294.

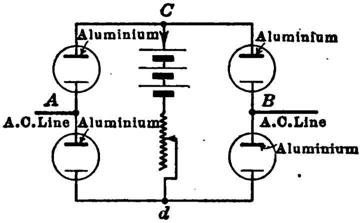

FIG. 295.

200. Charging by an Aluminum Valve.—If a jar is arranged as in Fig. 276 using an aluminum plate as one electrode, a lead or carbon plate for the other and a strong solution of baking soda (bicarbonate of soda) in water for the electrolyte, a rectifier is provided which works quite satisfactorily on small currents. Other chemicals may also be used with water for the electrolyte such as ammonium phosphate or any borate, but baking soda is mentioned because it is so easy to purchase.

When such a cell is included in an A.C. circuit, a film of gas forms on the aluminum plate and thereafter current will flow through the cell to the aluminum plate but will scarcely flow at all in the opposite direction. The result is that this can be used for a rectifier on e.m.fs. up to something like 300 volts. On a 110-volt A.C. circuit there will be about 35 volts D.C. available. Less than half of each cycle of A.C. is used. Using a rheostat the charging current can be held to a desirable amount. For charging, the aluminum plate must be connected to the + terminal of the battery.

The action is fairly independent of the size of the electrodes and their distance apart. On account of the heat generated in the valve the electrodes should be put fairly near each other and either a considerable amount of electrolyte used so it will heat slowly, or the whole thing kept cool by a water circulation around it. If such apparatus is connected as shown in Fig. 295 quite a steady charging current can be obtained. When line *A* is positive, for example, current flows up through the valve, down through the battery as a charging current and out at *B*.

QUESTIONS AND PROBLEMS

1. A certain lead cell (*A*) has an e.m.f. of 2 volts and internal resistance of 0.02 ohm; another (*B*) has the same e.m.f. but an internal resistance of 0.04 ohm. The normal current for both is 5 amp. (*a*) Calculate P.D. of each when half normal, normal, and twice normal current is flowing in discharge (six values). (*b*) Calculate P.D. of each when the same currents are flowing but the cells are charging (six values). (*c*) Explain how it might be that two cells with the same normal charging rate, have such different internal resistance.

2. A certain maker of lead cells gives 0.01 ohm as the internal resistance of a cell using plates 6 in. by 6 in. in size, when two negatives and one positive are in use. What will be the resistance of a cell having four positives and five negatives of the same size made by the same company? (The distance between plates will be the same. Consider simply the number of paths for current and the relative area of this path for the two cells.)

3. A certain cell made by the Electric Storage Battery Company, has five rows of peroxide buttons (see Fig. 281) eight per row, and four rows containing seven buttons per row, in the positive plate of a cell to give 40 amp.-hr. at normal rate, using two negatives properly proportioned. What would be the normal discharge current for a cell containing seven positives and eight negatives? In another cell of the same kind the positives have plugs like the one first named, but they are set 16 in a row and 17 rows are used. The negatives are properly proportioned. There are 10 positives and 11 negatives. What capacity has this cell? (Capacity and active material are proportional.)

4. A set of Edison cells in series has been discharged at normal rate of 30 amp. in 5½ hr.; they were then recharged at normal rate in 7 hr. What is the capacity of the battery in ampere-hours, and what is the ampere-hour efficiency?

5. A set of 62 cells (lead) all in series, is charging at the normal rate of 20 amp. Their back e.m.f. has reached 2.05 volts each. Their internal resistance is 0.008 ohm each. How many volts is the applied e.m.f.? How many volts must this be increased in order to increase the current to double the normal?

6. A set of 62 lead cells has a capacity of 320 amp.-hr. on a constant-potential 110-volt system. When fully charged, the s.g. of the electrolyte was 1230; at discharge it is 1180. The cells are discharging and s.g. measurement shows that the electrolyte now stands at 1200 s.g. How many ampere-hours capacity still in the cells?

7. A set of 16 lead cells all in series is charging at the normal rate of 15 amp. with 34 volts at the terminals of the set. The current is taken from a shunt dynamo directly connected to the batteries.. What is the e.m.f. of each cell? To what terminal voltage will the dynamo drop to have 15 amp. of discharge current flowing to drive it as a motor? Prove that it would continue to revolve in the same direction. (Assume that with normal current there is a drop of 0.03 volt due to the resistance of each cell.)

8. A set of three lead cells on an automobile has a capacity of 80 amp.-hr. as used for starting and ignition work. It is to be charged from a 110-volt D.C. circuit at a constant current of 6 amp. (the proper amount). At 10 c. per kilowatt-hour calculate the cost of current for charging and the amount of resistance to control the current so that when charging is begun the current above stated will flow. Assume the e.m.f. at time charging is begun to be 2 volts per cell and the internal resistance such that on normal current there is 0.04 volt drop in each cell. Allow 90 per cent. ampere-hour efficiency.

9. A certain automobile starting battery rated at 80 amp.-hr. on a 4-hr. discharge, is called on for 200 amp. to pull the engine over and start it. It does this for an average time of 6 sec. each time the engine is started. Assume that it is used only for this purpose and that the starting is not done so often but that the whole capacity of the battery is available. (For this the whole discharge must not occur in less than 4 hr. and even intervals between use occur.) How many starts may be made on one charge?

10. A set of 48 vehicle lead cells having a normal capacity of 250 amp.-hr. at a 4-hr. rate is to be charged by direct connection to a 110-volt line. Their e.m.f. is at 1.9 volts each and when nearly charged it will be at 2.28 volts each. If we count the resistance of the cells constant at 0.001 ohm throughout charge, what will be the charging current (*a*) at beginning of charge; (*b*) near the end of charge when e.m.f. has reached the value stated? (*c*) Make a diagram to show how they are connected.

CHAPTER XVII

ELECTRIC LIGHTS

201. The Production of Light.—Commercial electric lights are produced by the heating effect of current in one of two ways.

A slender conductor has enough current sent through it to bring it up to a white heat and so to a condition in which it gives out light. It is at an incandescent temperature and is called an incandescent electric light.

At a certain point in a circuit two conductors are separated while current flows through the path of which they form part. As the contact area diminishes the temperature rises locally until as the conductors separate, one or both of them are at a temperature high enough to give off conducting vapor. Through this vapor path the current continues to flow in an arc. The arc, the ends of the conductors which separated (called electrodes) or one of them, becomes luminous due to the heating effect present; and an electric arc light is produced.

It will be the purpose in succeeding sections to briefly study the most important features of both types of light.

202. Successful Lights.—To be useful any kind of electric light must satisfy most if not all of the following conditions:

(*a*) Must be less expensive than other forms of artificial light or have some merit which brings it into use regardless of cost.

(*b*) Must give a light of desirable color and one which is steady.

(*c*) Must be easy to control; to start or to turn off. Must be noiseless.

(*d*) Must be durable and easy to care for.

203. Definitions and Terms.—*Candlepower.*—When we speak of a light having a certain candlepower, say 20, we mean it gives a light twenty times as much as that given by a candle.[1] The candlepower (abbreviated cp.) of a light is not the same if viewed from different directions. The more the area of light giving material seen from any direction, the more the candlepower in that direction. By horizontal candlepower is meant the candlepower of a light in the horizontal direction; if the light given in different horizontal directions is not the same, it is the average candlepower in this direction. For incandescent electric lamps of the ordinary forms, the term horizontal candlepower applies when they are so placed that their long axis is vertical. Mean spherical candlepower is the average candlepower of a light in all directions. The reduction factor is a number by which to multiply horizontal candlepower to get mean spherical candlepower.

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[1] Once a certain prescribed sperm wax candle, but now a unit maintained between the national laboratories of America, England, and France by means of groups of incandescent electric lamps which are seasoned to make them constant and then compared at frequent intervals, the candlepower of any one thus being known.

Lumen.—It is becoming usual to speak of the light a source gives in direct terms, and not by the use of the term candlepower. Out of any source light streams into space; what we mean by candlepower is merely how many times as much light streams in a given direction as streams from a candle. The lumen is the unit in which light is measured. Imagine a 1-cp. source of light at a point giving the same light in all directions; that is having the same candlepower in all directions. Such a light is said, for certain mathematical reasons, to have 12.56 lumens pouring out of it. It has one mean spherical candlepower. Hence in general

$$\text{Mean spherical candlepower} \times 12.56 = \text{lumens}$$
$$\text{Lumens} \div 12.56 = \text{mean spherical candlepower.}$$

An incandescent filament with a fixed amount of current through it to hold it at constant temperature, might be stretched out in a line or doubled up in coils of different form; and except for the loss due to one turn of coil cutting off the light from others, the mean spherical candlepower of the source, and the lumens it gives are the same; although the lumens in a given direction might vary greatly as the form of the filament was altered.

Efficiency.—By the efficiency of a light is meant the watts it uses per candlepower produced, or the lumens per watt. The smaller the number giving the value of watts per candlepower, the higher the efficiency; that is the more economical is the source in its use of light. Thus if a source has an efficiency of 4 watts per candlepower or 3.14 lumens per watt it has low efficiency. If

½ watt per candlepower or 25.12 lumens per watt it has very high efficiency. Notice that $\frac{12.56}{\text{lumens per watt}}$ = watts per candlepower or $\frac{12.56}{\text{watts per candlepower}}$ = lumens per watt. Commonly, however, the term watts per candlepower is used of horizontal candlepower even when not stated; while lumens per watt is always irrespective of direction.

Life.—By the life of a lamp is usually meant the number of hours of useful life rather than the total hours it will burn before it gives no more light. It is a term used particularly with incandescent lamps; but for them does not necessarily mean the hours burned until the filament breaks. Originally the idea of useful life was derived from the fact that as lamps get older, the light they give becomes less, while the current continues much the same as at first. It does not pay to keep a lamp burning then after it becomes dim although the original cost of the lamp is an important factor in determining when to stop using it. It is generally conceded to-day that incandescent lamps have reached the end of their life (and so the "smashing point") when their candlepower has diminished to 80 per cent. of the initial rated value, whether the filament has then broken or not.

204. Incandescent Lamp Filaments.—Carbon and tungsten are the materials used for filaments of successful incandescent lamps.

Carbon filaments are made of liquid cellulose (woody fiber) squirted into alcohol to form a thread which when properly shaped is carbonized. Such a filament is said to be "untreated." When immersed at red heat in gasoline vapor, a graphite coating is deposited on the base carbon and the filament is said to be a "treated" filament. If the base carbon was subjected to very high temperature in an electric furnace and after "flashing" in gasoline vapor was baked again at the furnace temperature, the filament is said to be "metallized." Lamps with such filaments have very little use to-day. They have been so far surpassed in efficiency, maintenance of candlepower during life, etc., that it is only where efficiency is of no importance and the advantage of high resistance in compact space is important that they are used.

Tungsten is a rare metal which, under elaborate investigation, it has become possible to secure in such condition that it can be drawn into a wire slender enough to serve as a lamp filament. In some lamps the filaments are less than a thousandth of an inch in diameter. It has a high melting point (3200°C.) and can be maintained very white hot for long periods without much evaporation or deterioration. Using it a higher efficiency is secured than by the use of any other incandescent filament, and the difficulties in manufacturing it and placing it in lamps have been so overcome that it is the one important filament to-day.

Figs. 296 and 297 show incandescent lamps with filaments respectively of carbon and tungsten. The carbon filament is rigid enough to be self-supporting even when white hot; the tungsten wire softens and must be better supported by wires forming spoke-like projections from a glass hub.

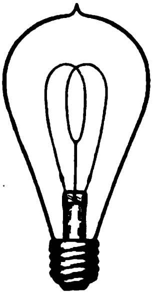


Fig. 296.

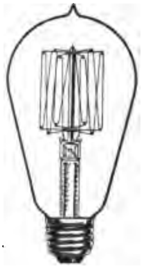


Fig. 297.

205. General Features of Construction.—Incandescent electric lamps have certain features of construction common to all or nearly all types. They have an all-glass enclosing globe and leading in wires of platinum to make a perfect seal at the points where current enters or leaves. The platinum wires are usually very short pieces within the glass to which copper wires are welded on each end. In the lamp these wires must be designed so that the sudden heating of the filament at lighting, does not cause the wire to expand and crack the glass around the seal, while on the other hand it must not carry away too much heat. Nearly all incandescent lamps have a high vacuum inside the bulb, so that the hot filament will not be acted on chemically by the gas there; but more, so that the heat of the filament is not conducted away by the gas. A vacuum is a good heat insulator. Nearly

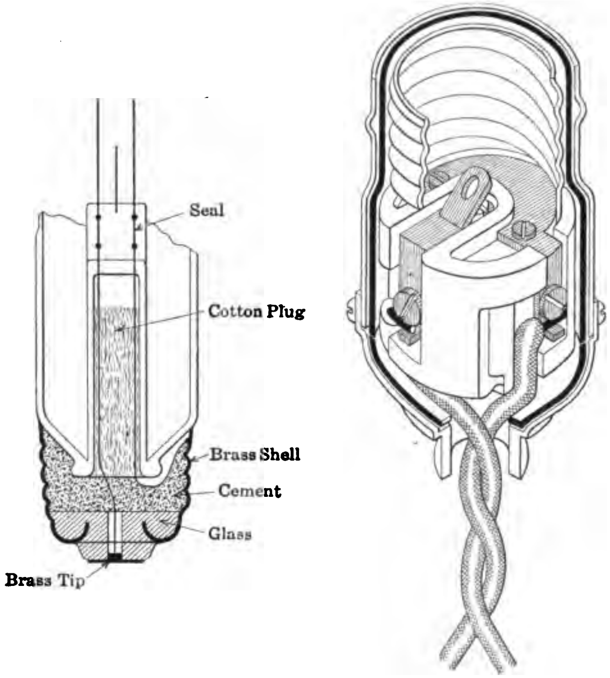


Fig. 298.—A lamp base is shown in section at the left. An ordinary keyless socket is shown in section at the right. The path for current from the positive side of the circuit to the negative through the lamp filament, when the lamp is screwed into place, can easily be traced.

all incandescent lamps have a screw base (called an Edison base), one leading in wire terminating on the metal screw-threaded portion (see Fig. 298); the other on the brass tip insulated from the shell by a glass plug. In Figs. 296 and 297 such bases are shown. Another feature of construction common to incandescent lamps is the high-resistance filament. A 40-watt 110-volt lamp for example, has a resistance of 302.5 ohms. Since incandescent lamps all operate by the heating effect of current, they are all equally available for A.C. or D.C. circuits. A lamp used on either circuit at the same e.m.f. takes the same current and consumes the same watts.

All incandescent lamps do not have filaments of the same brightness. The color and brightness of the filament are related to the temperature at which the lamp operates. Tungsten lamps are more than three times as bright as carbon lamps when both are operated at temperatures normal for them. They have something like 1000 cp. per square inch of light-giving surface.

206. Gas-filled Lamps.—The most recent development of tungsten lamps is that which uses nitrogen or some other inert gas in the bulb at ordinary atmospheric pressure and a filament coiled in helical spring-like form as shown in Fig. 299. The presence of the gas prevents rapid evaporation of the filament even when heated to a very white-hot temperature. The advantage thus obtained, more than offsets the disadvantage of large heat loss by the heat conduction through the gas to the glass bulb and to the outer air. This loss is reduced by arranging the filament in a compact form. Only lamps for larger candle-powers are made this way. The bulb temperatures of these lamps in operation will be as high as 220°F. for the smaller sizes to 350°F. for the largest.

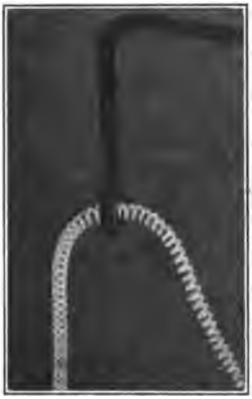


Fig. 299.

207. Special Forms of Lamps.—Large numbers of incandescent lamps are used in series connection. Some are in strings of five or six on railway circuits. In such case the same current passes through all the lamps of a series and for equal incandescence the filaments must be of the same diameter. Special care is therefore taken in making lamps to be used this way.

Some lamps are made to operate in series on constant-current D.C. or A.C. circuits for street lighting. Such circuits are usually supplied with A.C., the amount of current being 4 amp., 6.6. amp., or 20 amp. Such lamps have short tungsten filaments, deliver large candlepower, and are made with filaments in the helical form shown in Fig. 299.

Mazda lamps are tungsten lamps of any of the forms earlier described, made by the various lamp works of the General Electric Company, and their licensees.

Lamps described in section 206 and the series lamps for street lighting are called type C Mazda lamps; regular and railway tungsten lamps (vacuum-lamps as in Fig. 297) are type B Mazda lamps.

Candelabra, decorative, novelty, electric automobile lamps are all made with carbon or tungsten filaments and embody the methods of construction already described. Very small, low-voltage lamps operate at lower efficiency than larger ones on account of the cooling effect which the leading in wires exert on the whole filament.

208. Incandescent-lamp Performance.—The efficiency of commercial tungsten lamps in present practice may be illustrated by the following figures for much used sizes. Carbon filament lamps have efficiencies of 2.5 to 3.5 watts per candlepower.

Lamp	Circuit	Watts	Watts per cp.	Horizontal cp.	Reduction factor
Mazda multiple Type B	105 to 115 volts	40	1.03	38.8	0.78
	105 to 115 volts	100	0.95	105.0	0.78
Mazda multiple Type C	105 to 125 volts	100	0.80	125.0	0.80
	105 to 125 volts	300	0.70	429.0	0.80
Mazda street series. Type C	6.6 amp.	72	0.72	100.0	....
	6.6 amp.	367	0.61	600.0	....

Tungsten lamps when operated under usual circuit conditions and according to their rating will show a life of from 1000 to 2000 hr. of burning. The life curve is much the same for all incandescent lamps, no matter what the material used in the filament. Fig. 300 shows this for a type B tungsten lamp. The performance is the same on either A.C. or D.C. On low-frequency circuits a flicker of light begins to show. High-efficiency lamp filaments heat and cool rapidly.

Any incandescent lamp burned "over voltage" will give a whiter light, but run a considerably shorter life at higher efficiency. At undervoltage, the life is longer, the color is less white, and the efficiency disproportionately reduced. Lamps are best operated at a constant voltage (or current) and at the figure recommended by the maker; not that which is nominal for the circuit, but that actually given the lamps. Very common values of e.m.f. for multiple circuits are 110 and 220. A better selection of lamps is usually possible by avoiding lamps marked with these special figures.

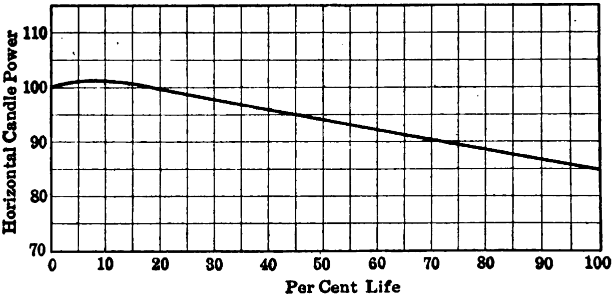


Fig. 300.

Lamps marked for a certain number of watts are not necessarily exactly true to this marking. Individual lamps of the usual sizes, should all show a total watt consumption at marked voltage between 8 per cent. above and the same amount below the marked value.

Incandescent lamps are used because they satisfy conditions *b*, *c*, and *d* of section 202. They are themselves devoid of fire risk; the substitution of one size for another is simple and something anyone can do; such lights are considered "up-to-date." Besides this, temporary or permanent extensions of service are easy to make; while the availability of the same circuit connections for heating appliances and small motors gives an extra value which is well recognized.

209. Electric Arc Lamps.—Such lamps are made to utilize the light which is secured by separating two parts of a circuit through which current is flowing, thus drawing an arc as mentioned in section 201. The arc may be formed between the tips of carbon rods, the source of light being the white-hot ends of the rod; or it may be formed between inpregnated carbon rods or electrodes, such that the arc itself is very luminous.

The mountings of the carbons and the necessary mechanism to start, hold and feed the arc, complete a lamp. There is only a restricted field for such lamps and those using carbon rods with white-hot ends are rapidly being displaced. The principles of operation are of such importance, however, that a brief outline is given.

210. The Carbon Arc.—This is the arc formed between the separated tips of carbon rods made from petroleum-coke or lampblack. The fine powder is mixed with a sugar syrup into a stiff dough. It is then forced through a die of the proper size and baked or recarbonized. Uniformity of material is very important if steady light is desired. The rods must be very straight and of uniform diameter. A.C. lamps burn very badly unless one carbon at least is cored. A cored carbon is one made like a thick-walled tube, after which a soft graphite and carbon mixture is used to fill the hole in it. This mixture volatilizes readily and maintains the arc when the A.C. passes through its zero values.

The color of the light given closely resembles daylight; the arc burns silently when of proper length; the carbon is very infusible and the result of its burning is the formation of a harmless gas; the carbon rods are poor conductors for heat and a big temperature difference is maintained between the ends where the arc forms, and other parts of the rods.

The arc itself is a stream of glowing carbon vapor of somewhat purple color. A D.C. arc open to the air, has both carbons burned to a conical form due to the ascending column of air around them (see Fig. 301). The upper tip is at a very white heat, about 4000°C., and has a crater-like form; while the lower tip is less hot but incandescent where the arc stream stops. About 80 per cent. of the light comes from the crater. The light comes from a very small area; 50,000 to 70,000 cp.

per square inch would be found, varying with the carbons used. It is this very fact of producing a very powerful light of good color almost at a point that gives this arc its present importance.

An alternating-current arc with the same current gives much less light, both carbon ends being heated equally. With every reversal of current a white-hot crater forms and then as current dies out and reverses the carbon ends cool down, and as it starts in reverse direction a crater is formed on the other carbon end. In a D.C. arc the positive carbon burns away twice as fast as the negative if they are of the same size and material. In an A.C. arc they burn at nearly the same rate.

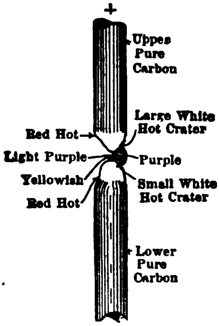


FIG. 301.

A D.C. arc will hiss when short and flame when long, but at proper length (say $\frac{1}{8}$ in. for a 10-amp. current with $\frac{7}{16}$-in. carbons) using about 45 volts, it burns silently. An A.C. arc is always noisy, the tone emitted being determined by the frequency of the current. 45 volts on the arc with 10 amp. would be normal for it.

211. Forms of Carbon Arc Lamps.—Those in which the carbons are exposed to the air may be hand feed lamps, used in projection lanterns and for search lights. In them the carbons are drawn apart, given proper alignment, or fed toward each other by a hand-operated screw feed. The screw is usually so cut that one carbon rod is moved twice as fast as the other. It must be so for D.C. lamps, for in this way the crater is kept at the correct point to give the desired light projection.

In other lamps for general lighting, the carbon ends where the arc forms are in a glass enclosure arranged so that almost none of the air around the lamp can reach the hot carbon ends. When the lamp goes into operation the air in the enclosure rapidly parts with its oxygen, which forms carbonic acid gas there; and thereafter the carbons burn away very slowly, as the result of the vaporization of the carbon tips in the arc. The carbons burn with very blunt ends in such lamps, and to let the light out the arc is drawn at least ⅜ in. long. This makes the volts across the arc 75 or more. It burns fairly steady, however, because of the absence of air currents within the enclosure. Such a lamp is shown in Fig. 304.

Open carbon arc lamps use currents of from 6–60 amp. and have 45–55 volts across the arc. Enclosed carbon arc lamps have 3–7 amp. through them with (usually) 75–80 volts across the arc. D.C. lamps use 2–3 watts per mean spherical candlepower. Alternating-current lamps have a power factor from 0.6 to 0.8 and use about 3.5 watts per mean spherical candlepower.

212. Typical Arc-lamps Mechanisms.—All automatic lamps must have a means of starting the arc, of keeping the arc burning and of feeding the carbons to maintain a constant steady light. Arc lamps are used on constant-potential circuits in parallel; while on constant-current circuits they are connected in series. Two essentially different types of mechanism are used. The principles embodied in them hold for all arc lamps.

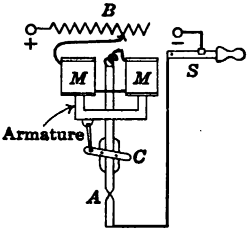


Fig. 302.

Fig. 302 shows a diagram of the mechanism for a lamp like that shown in Fig. 304. Such a lamp is built to work on a constant-potential circuit and to regulate for constant volts on the arc. When the switch *S* is open the magnet armature is down, the clutch *C* is open, and the carbon rods rest on each other at *A*. The magnets are in series in the circuit; Fig. 303 shows the clutch they operate in detail. When current is turned on the lamp by closing the switch, current flows in through the ballast *B*, through the magnet coils *MM*, down the carbon rods and out through the switch *S*. The current which flows causes the magnet to lift its armature, closing the clutch on the upper carbon and raising it so as to strike the arc. As the upper carbon rises, the resistance of the lengthening arc causes the current through the circuit to decrease; and this continues until the amount of current flowing is just enough to cause the upward pull of the magnet to balance the downward pull of gravity on the upper carbon, the armature and their attachments. The lamp then burns if on 110 volts, with 75 volts on the arc, 3 to 5 volts on the magnets, while the remainder is lost in the ballast.

As the carbons burn away the lengthening arc causes the current to diminish further, thus weakening the magnets and allowing the upper carbon to move slowly downward, until at some point the clutch slips, the carbon slides through it, the increase of current causes the magnet to pick up its armature again and the arc is fed.

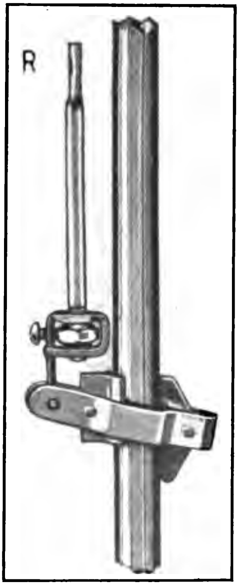


Fig. 303.

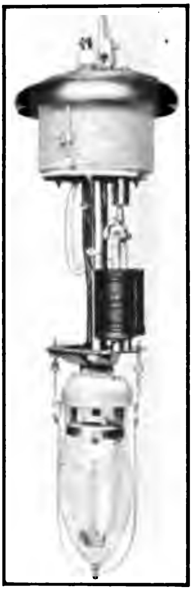


Fig. 304.

The lamp described is a D.C. lamp; ballast *B* is simply some electrical resistance wire, usually placed within the upper part of the case. It is always included in order to use up the volts not taken by the arc and mechanism. It also prevents large current changes through the lamp as the carbons separate to the proper distance for operation. In an alternating-current lamp this would be replaced by a choke coil; that is, an iron core on which a coil of copper wire is wound. The inductance of this coil takes the place of the resistance used in the D.C. lamp without the loss of energy it occasions.

The type of mechanism usual for constant-current circuits where lamps work in series may be illustrated by Fig. 305. Magnet *M* is wound with coarse wire in series with the arc, *m* is a magnet of fine wire placed below it. Between the magnets is the armature *A* subject to the attraction of both. When no current is on the lamp the carbons are together, the armature is down, and contact *C* is closed. When current is turned on, two alternative paths are open for current to flow. One is from the positive terminal through the carbons and magnet *M*, the other through the contact *C* and resistance *R*. Resistances are so proportioned that enough current passes through *M* to cause it to lift the armature, opening contact *C*. As it rises further it causes the clutch to grip the upper carbon and raise it. The arc is thus struck. As the carbons separate, current begins to flow in increasing amount through the shunt magnet *m* which had no current in it, while the carbons were together. The increasing pull it exerts along with that of gravity soon comes to balance the upward pull of *M*. The armature is then stationary and the arc burns quietly. When the arc gets abnormally long the shunt magnet becomes powerful enough to pull the armature down until presently the clutch lets go and the upper carbon feeds.

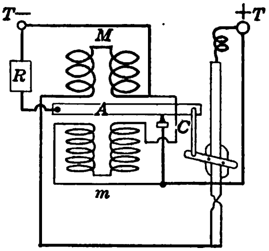


FIG. 305.

In any lamp worked on a constant-current circuit in series with other lamps provision must be made to have some shunt device so that if the lamp mechanism fails the circuit is maintained and other lamps continue to burn. For this reason the contact *C* was provided. An open circuit in the lamp will cause this to close and the current through other lamps be uninterrupted. This device is called the cut-out.

When several lamps are burned in series from a constant-potential circuit, a cut-out is provided on each; but instead of a lamp being short-circuited when the cut-out operates, the arrangement is such that enough resistance is put into the circuit to hold the current through the other lamps unaltered. For arc lamps working in series a shunt magnet and a differential pull such as it produces is necessary; for those in parallel supplied with constant potential a simple mechanism with series magnet is common.

A dashpot is always attached to the magnet armature to steady the operation of the mechanism and prevent sudden changes in position of the armature or even rupture of the arc at starting. Frequently the piston is of graphite for the sake of automatic lubrication. The current is always conveyed to the upper moving carbon of an arc lamp by a flexible wire connected from a fixed portion of the lamp to the carbon holder, never through rubbing contacts. It is often a bare strand of wires, on which a lot of glass beads are strung to provide the insulation. A 12-in. carbon is usual for each trim, the stub being used for the negative electrode. For an A.C. lamp one of the carbons is always cored. A reduction in diameter of carbons on a given lamp results in securing much more light for the same current. The ballast on constant-potential arc lamps is always planned to be very durable. If of resistance wire it is made large enough not to overheat when the largest current flows; that is, when the carbons stick together and will not separate. It has been common to design lamps so that by the interchange of inductance for resistance, a D.C. lamp can be transformed to use it on A.C. Resistance and inductance types of ballast are always so arranged that the amount in circuit can be adjusted. This permits adjustment to circuits of different e.m.f. and also supplies the means for adjusting the voltage on the arc. The more volts on the arc the higher the efficiency of the lamp, but if this is carried too far the lamps become unsteady in operation.

The magnets are wound using a size of wire which will not become dangerously hot under extreme conditions, on a spool which is split longitudinally if of metal, so that A.C. will not cause eddy currents to flow and heating to result. Often the magnet spools or the magnet armature or both are spring-supported when the lamp is for A.C., in order to suppress the noise resulting from the pulsating pull. To adjust for larger current a tap along the series magnet is often provided. With less turns on the magnet the lamp takes more current. A heavier weight on the armature or on the moving carbon produces the same result. The iron armature is laminated in A.C. lamps.

213. Flame Arc Lamp.—A flaming arc is formed between the ends of carbons impregnated with metallic salts. Particles of these salts are heated to brilliant incandescence in the arc. Calcium fluoride is commonly used, the amount in the carbon being sometimes as much as 25 per cent. of the total. The light from a lamp using carbons thus impregnated is reddish yellow; if barium and titanium are used, the color of the light is white. The temperature of the arc is lower than that between carbon ends and so the tips are not so hot. The amount of light from

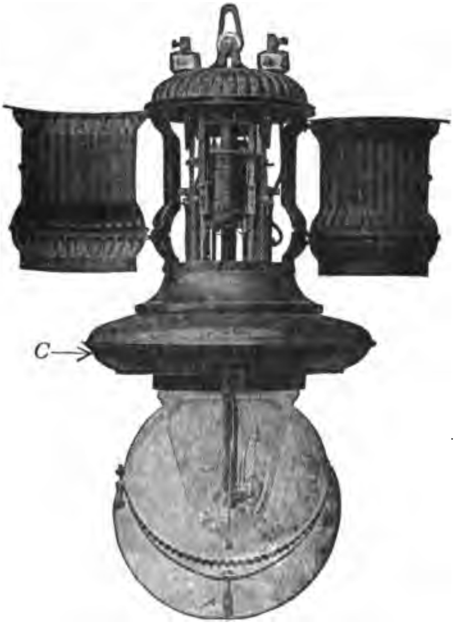


Fig. 306.

a yellow flame is so great as to work at about 0.45 watts per mean spherical candlepower.

From such an arc fumes rise which must be carried away from the glass of the inner globe which would be obscured by them, and kept from metal parts which they attack chemically in the presence of moisture. The products from the hot arc rising in a fine powder make these fumes. They are carried by the ascending hot gas current up into a condensing chamber at *C* in Fig. 306 where they are deposited. The cooled and clean gases pass down over the surface of the inner globe to return again carrying the products of the arc up to the condensing chamber. This chamber is entirely separated from the mechanism box.

Immediately above the arc there is a piece of refractory insulating material called an economizer, shaped like an inverted cup. This holds the hot gases in the arc, increasing the life of the carbons; while, since the fumes always keep it coated very white, it helps to improve the light the lamp supplies. A little blow coil just above the economizer holds the arc down to the carbon ends. Should slag form at the carbon tips it may interpose enough insulation to make trouble in starting the lamp.

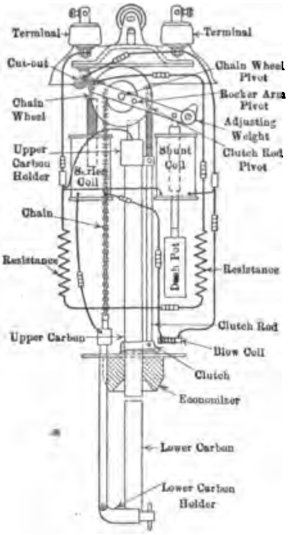


FIG. 307.

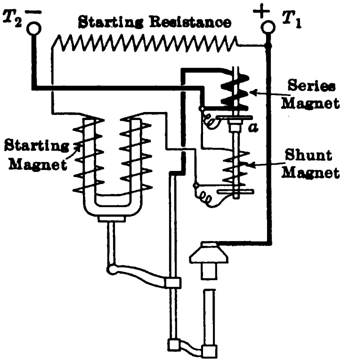
The mechanism is similar to Fig. 302 for constant-potential lamps or to Fig. 305 for constant-current lamps. That shown in Fig. 307 is for a constant-current lamp. Here a series and shunt coil are pulling against one another through the medium of a rocking lever. In order to keep the arc always just below the economizer both carbons have to move; the downward feed of the upper carbon being accompanied by an upward feed of the lower. The proper relative motion is secured by the arrangement of the chain wheel shown in the figure. The lamp here shown uses carbons 7/8 in. in diameter and 14 in. long. A current of 10 amp. is used with 55 volts on the lamp (50 on the arc) and on A.C. work with a power factor of 0.8.

214. The Magnetite Arc Lamp.—The magnetite, metallic flame, or luminous arc is formed between electrodes one of which is copper and the other a tube of thin sheet iron containing an impalpable powder of magnetite (the magnetic iron ore). In addition there is said to be some oxide of titanium present to make the arc more luminous and oxide of chromium which on account of its high melting point prevents too rapid waste of the electrode. The arc keeps the iron tube sealed at the end. A 4-amp. arc with about 70 volts between electrodes is common, using a 7/16-in. arc length. It is the material from the negative electrode which produces the light. The current always passes from the copper to the other electrode. The arc is open to the air and the fumes which pass off from it are carried up through a chimney in the center of the lamp. It is not, therefore, a lamp for use indoors. The light is very white, the efficiency being about 1 watt per mean spherical candlepower. The electrodes are comparatively cool during operation of the lamp. It is used only on D.C. or rectified A.C.; for the arc will not reëstablish itself on reversal of alternating current.

Fig. 308 shows a picture of such a lamp and a diagram of connections beside it. In the lamp will be recognized features of mechanism already described. Were the globe shown in place a metal pan would be seen placed to catch fume deposits and any hot particles which drop from the arc.

The carbons are separated when the lamp has no current through it and so the method of operation is slightly different from any heretofore studied. The mechanism of the constant-potential lamp is very easy to understand. That for operation on constant current is shown in the diagram. Its method of operation follows. Before current is admitted to the circuit the carbons are separated and a contact at *a* is closed. Current through the circuit flows from T_1 through starting resistance, starting magnet and short-circuit on shunt magnet (contact *a*) to T_2. The starting magnet lifts its armature which closes the circuit through the carbons.

The series magnet now receiving current through the carbons picks up its core, opening contact *a*. The shunt magnet is thus thrown into circuit and increasing the resistance through the starting magnet circuit causes it to feed the arc. As the arc burns, the current through the starting and shunt magnets in series gets larger, for they form a shunt to the increasing resistance of the arc. Since the circuit has constant current, the series magnet has the current in it diminishing. The result is that the current in the shunt magnet is rising until contact *a* closes. Immediately the starting magnet receives enough additional current to pull up on its armature and the arc is fed. It must be understood that a simple detent device holds the lower carbon from sliding down more than a long arc length from the upper when the clutch connected to the starting magnet lets go.



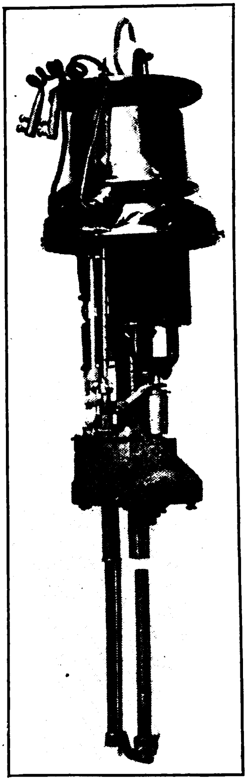


Fig. 308.

Lamps are made at present for 4, 5, or 6.6 amp. using 75 volts on the arc. With 11/16-in. by 9½-in. magnetite electrodes they burn 100 to 300 hr. per trim, depending on the amount of current used.

215. Current Supply for Series-lighting Circuits.—Commercial dynamo circuits are arranged to work at constant potential. If constant current is required, special apparatus must be used. Certain of the most common arrangements will be described.

By the use of a transformer like that in section 135, a constant current at variable voltage may be secured. Under variation of resistance in the circuit the current remains practically unaltered, the e.m.f. varying to meet the necessary conditions. Incandescent lamps may be connected in a single series on such a transformer. Since the burning out of any lamp would open the whole circuit, it is necessary to provide means to prevent this. At each lamp there is therefore installed a film cut-out or a shunt reactance. A film cut-out is a thin piece of insulation which will fail with 350 or 400 volts across it, placed between conducting pieces, one of which is connected to one terminal of a lamp, and the second to its other terminal. Should the lamp fail, the whole voltage of the circuit is applied to the film; the film breaks down and the lamp is thus short-circuited and the circuit kept in operation. A shunt reactance is a coil on an iron core which shunts a lamp. The reactance is great enough so that very little current will be diverted from the lamp. Should the lamp filament break the whole current flows through the shunting coil, but no greater rise of potential across lamp terminals occurs for the counter e.m.f. due to the inductance does not change much. The current in the coil is considerably larger, but because of saturation of the iron on which the coil is wound the flux per ampere is much less and so the inductance is smaller (see section 115). Hence IX increases only a moderate amount. When arc lamps are operated from constant-current transformers, they are connected in a single series, using a type of mechanism similar to that shown in Fig. 305, including the individual cut-out for each lamp. A fault of this method of arranging a constant-current circuit lies in the fact that if the line open-circuits and falls to the street, the highest voltage of the secondary exists between the open ends. Safety devices are available to prevent this condition by short-circuiting the line or that part of it which contains the break.

Another method of arranging series circuits to operate at constant current is to connect in series with the lamps a coil into which a counter-balanced iron core is drawn by increasing current. The whole circuit thus made up is connected to a constant-potential source of 1100 or 2200 volts. A small increase in current resulting from reduction in load and of circuit impedance, causes the core to be drawn into the coil, thus automatically increasing its impedance and holding the current from more than a slight change even with large changes in line impedance.

A third plan for operating incandescent lamps in series is to connect a suitable number directly across a constant-potential circuit. The current stays practically constant even though some lamps should break their filaments. If this plan is used with a film cut-out on each lamp, an ammeter must be installed at the station and a bank of lamps be there provided to be turned successively into the circuit, as need arises, to hold the current to the proper value.

Direct-current series circuits for magnetite arc lamps are worked from mercury arc rectifiers. The principle of operation of a rectifier has been described in section 198. The arc-lamp circuit takes the same place as the storage batteries with virtually equivalent connections, while the bulb is somewhat changed in construction to suit high-voltage conditions. The bulb works from the secondary of a constant-current transformer, the whole apparatus usually being immersed in a tank of oil.

QUESTIONS AND PROBLEMS

1. On limited changes in voltage the changes in Mazda lamps are as follows:

Per cent. changes (increase)		
in voltage	in candlepower	in current
1.0	3.56	0.58

A Mazda lamp of 60 watts is in operation on a 120-volt circuit. It uses 1 watt per horizontal candlepower. Find (*a*) its resistance under normal conditions; (*b*) its candlepower and current under normal conditions; (*c*) its candlepower, current, and resistance when the circuit voltage drops to 117.6; and (*d*) when it rises to 122.4.

2. Referring to the table in section 208 calculate the mean spherical candlepower, the lumens, and the lumens per watt of each of the following: (*a*) 40-watt type B Mazda lamp; (*b*) 100-watt type B; (*c*) 100-watt type C.

3. A certain room may be lighted by using four fixtures. The total horizontal candlepower of the lamps should be about 1200. Either 100-watt or 25-watt type B Mazda lamps may be used. Which would be preferred and why? Consider (*a*) cost per hour of operation; (*b*) appearance; (*c*) cost of installation. Use a practical fixture arrangement for each size of lamp.

4. The type B Mazda lamp when hung vertically with base above gives 1/6 of its rated candlepower downward. Type C lamps give 40 per cent. of their rated candlepower downward. Why this difference? Calculate downward candlepower for 100-watt type B and for 100-watt type C lamps.

5. It is desired to so control the lamps lighting the room referred to in problem 3, that with a certain fixture arrangement the light can be cut to one-third its total amount by turning off two-thirds the lamps at each fixture. Make an outline diagram for this allowing no more than 660 watts per circuit from the panel board and controlling the lights through the least practicable number of push switches mounted on the wall of the room.

6. Thinking of a simple D.C. 5-amp. constant-potential arc lamp and mechanism like that shown in Fig. 302, (*a*) calculate the amount of resistance to use for the ballast if 76 volts are used on the arc, and 4 in the magnet; the applied e.m.f. is 120 volts. (*b*) Why will reducing the number of turns in the magnet winding cause the lamp to take more current?

7. For a series A.C. 6.6-amp. arc (*a*) why is a ballast unnecessary; (*b*) what would be the effect on the performance or condition of operation of the lamp if a lead weight were hung on the armature *A* (see Fig. 305)?

8. Two flaming D.C. arc lamps are worked in series across a 220-volt circuit. The current they use is 5 amp. Calculate the number of ohms for a ballast resistance, so that the cut-out on one lamp when in trouble may throw it into circuit and the other lamp burn without change in current.

9. A 100-watt type B Mazda lamp, marked 110 volts, is true to its rating. It is installed on a 110-volt circuit where it receives low voltage resulting from 5 per cent. line drop. For each per cent. drop in applied volts, a Mazda lamp receives 1/5 per cent. less current and drops 3.5 per cent. in candlepower. Calculate the cost per candlepower for 1000 hr. when the lamp has 110 volts at its terminals and compare the cost when operated from the circuit as stated above. Current is to be taken at a residence rate of 10 c. per kilowatt-hour.

10. A certain store has in it five 5-amp. constant-potential arc lamps on a 110-volt D.C. circuit. Carbons cost 3 c. each and one must be supplied every 125 hr. The cost per trim per lamp for labor and repairs is 5½ c. The value of current (an isolated plant) is 6 c. per kilowatt-hour.

Type C Mazda lamps of 200-watt size can be purchased for $2 each. They last an average of 1000 hr. of burning and labor cost in placing lamps and cleaning them is 10 c. per lamp per 1000 hr. The m.s.cp. of the arc lamp is 225; that of the type C lamp about 215 so that one may fairly replace the other.

Neglecting fixture and original arc lamp cost, will it be less expensive to use type C lamps or not? (Calculate the total cost for 1000 hr. of burning of each lamp and compare results.)

11. Calculate the advantage (1) in total candlepower, and (2) in saving in cost, by replacing twenty 50-watt Gem lamps having a m.s.cp. of 16.5 each, by twenty 40-watt type B Mazda lamps having a m.s.cp. of 30.5 each. They are used in a building served by central station current at 10 c. per kilowatt-hour. The gem lamps last about 500 hr., but are supplied on a free-renewal basis. The Mazda lamps cost 25 c. each and have a life of 1000 hr. Calculate saving in cost on a 1000-hr. use of light, the two items being cost of current and cost of lamps. The labor cost on the installation is negligible.

12. A certain series incandescent A.C. street-lighting circuit has on it 100-cp. 5.5-amp. lamps. The P.D. on each lamp with this current is 13.1 volts. The lights are 176 ft. apart along a parkway 3 miles long. The pole line of No. 7 wire takes such a route that an extra mile of wire, 4 miles in all, completes the circuit through all the lamps. (*a*) What volts must be supplied from a constant-current transformer for this line when all the lamps are burning? (*b*) What rated kw. should be selected for this work? The sizes available are 5, 7½, 10, 15, etc. (*c*) If 10 lamps were suddenly to have the film cut-outs operate, what immediate per cent. increase in current would result and what e.m.f. would be on the line when the current is restored to its correct value? (*d*) Tell what plan you would use in starting such a circuit into operation. Consider the manipulation of things at the constant-current transformer. (*e*) If the line should open at some point what probable P.D. would be found between the ends at the break?

CHAPTER XVIII

WIRE AND WIRING

216. Wire Sizes.—Copper and alloy wires used in electrical work are drawn to a series of round sizes known by gage numbers in the American or B. & S. (Brown and Sharpe) gage. These sizes run from No. 0000 (four naught) the largest, which has a diameter of 0.46 in., to No. 36 which is 0.005 in. in diameter. Starting with the diameter of any size, that of the next smaller (called by the next larger number) is reached by multiplying by the number 0.890525. The best wire tables give the diameter of the various sizes to the nearest figures in the fourth decimal place. Wires smaller than those in the wire gage are designated by their diameter in mils or thousandths of an inch.

Another way for designating wire sizes is by stating their cross-section in circular mils. In order to determine the size this way, take the diameter of the wire in thousandths of an inch and square it. The result is the number sought. Thus for a 0000 wire, the diameter of which as stated above is 0.46 in.

$$460 \times 460 = 211{,}600 \text{ circular mils section.}$$

A mil is a thousandth of an inch. The result of squaring the diameter thus expressed is to produce a whole number which while not the real section is proportional to it. To get the real section (in square mils) simply multiply the circular mil section by 0.7854; for the area of any circle is obtained by the formula

$$\text{area of circle} = 0.7854d^2.$$

The value of this method of designation lies in the fact that it makes it very easy to compare wire sizes. If the circular mil section of one wire is half as much as another its resistance per foot will be twice as much as the other.

For the sake of the flexibility obtained by using a number of wires in a cable, many electrical conductors are made of a group of conductors of equal size "cable laid;" that is, arranged with one wire in the center surrounded by a group of six wires carried along with a slight spiral in one direction; the next layer is run with a reversed spiral, etc. Fig. 309 shows a cable end. In such cabling the strand is made of the central wire surrounded by a row of six; the next layer would contain twelve and each subsequent layer six more than the previous one. Thus any cable must have 7, or 19, or 37, or 61 wires, etc. A cable is designated by the cross-section of all the wires in it expressed in circular mils. To illustrate this take the following example of a cable having 200,000 circular mils section.

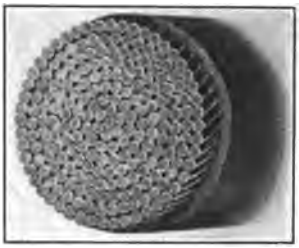


Fig. 309.

It might be made with a strand of 19 wires, in which case each wire must have a section of $\frac{200,000}{19} = 10,526 +$ circular mils. The diameter of each wire will thus be $\sqrt{10,526 +} = 102.6$ mils or 0.1026 in.; very close to No. 10 A.W.G.

Or it might be made with a strand of 61 wires in which case each wire must have a section of $\frac{200,000}{61} = 3278.7$ circular mils. The diameter of each wire will thus be $\sqrt{3278.7} = 57.26$ mils or 0.05726 in., very close to No. 15 A.W.G.

Either of the cables thus described has the same section, although one has 19 and the other 61 wires. They illustrate two sorts of stranding which are common in manufacture. The first represents regular stranding, the second flexible stranding. The smaller the wires in the strand, the larger is the cable for the same circular mil section, but the more flexible does it become.

217. Resistance of Wires.—The copper used in wire is not invariable in its conducting quality. This may be due to its having been annealed or not; or may depend on the exact purity of the material. The addition of very small percentage of metals, in themselves good conductors, will decrease the conductivity of copper. Copper is said to have 100 per cent. conductivity if in a wire 1 mil in diameter properly annealed, it measures 10.371 ohms per foot of length when at a temperature of 20°C. Commercial copper in wires of average size is very rarely less than 97 per cent. conductivity—that is, having a resistance of 10.692 ohms per mil foot (obtained by 10.371 ÷ 0.97). It is possible to have a conductivity higher than 100 per cent. Wire used for dynamo windings is often of such conductivity.

To determine the resistance of 1000 ft. of any size of wire having 100 per cent. conductivity call to mind the fact that resistance varies directly with length and inversely as section, and apply the formula

$$R \text{ per 1000 ft.} = \frac{R \text{ per mil ft.} \times \text{length in ft.}}{\text{section in circ. mils.}}$$

It has been inferred above that the resistance of wires increases with rise in temperature. The amount is 0.4 per cent. per degree C. rise in temperature. The increase in resistance due to location in a hot place or under atmospheric changes may be too great to be neglected (see also section 102).

In section 9 of Chap. I certain important facts were stated about the relative resistance of wires of different sizes in the American wire gage. These will be needed in connection with subsequent work. In addition it may be noted that if the resistance per 1000 ft. of one size is known, that of the next may be derived by dividing by 0.8 or multiplying by 0.8 according to whether the size is larger or smaller. Anyone who expects to do practical work with commercial wire should be able to determine by these approximate methods the approximate resistance of any size or length of wire or cable by a simple calculation and without the aid of a table.

In order to realize the relation between the resistance of 100 per cent. copper wire in commercial sizes compared with that derived by using the above principles note the following table:

Exact values from standard tables for 20°C. and 100 per cent. conductivity			Approx. values starting from No. 10–10,000 c.m. and 1 ohm per 1000 ft.	
Gage no.	Circ. mils section	Ohms per 1000 ft.	Circ. mils section	Ohms per 1000 ft.
0000	211,600	0.04901	200,000	0.0500
000	167,800	0.06180	160,000	0.0625
00	133,100	0.07793	128,000	0.078
0	105,500	0.09827	100,000	0.100
1	83,690	0.1239	80,000	0.125
2	66,370	0.1563	64,000	0.156
3	52,640	0.1970	50,000	0.20
4	41,740	0.2485	40,000	0.25
5	33,100	0.3133	32,000	0.31
6	26,250	0.3951	25,000	0.40
7	20,820	0.4982	20,000	0.50
8	16,510	0.6282	16,000	0.625
9	13,090	0.7921	12,500	0.80
10	**10,380**	**0.9989**	**10,000**	**1.00**
11	8,234	1.261	8,000	1.25
12	6,530	1.588	6,250	1.60
13	5,178	2.003	5,000	2.00
14	4,107	2.525	4,000	2.50

The last two columns of this table are made according to the following plan. Starting from No. 10 for which the data is given

For No. 9 $\frac{10{,}000}{0.8} = 12{,}500$ c.m. $1.00 \times 0.8 = 0.8$ ohms

For No. 11 $10{,}000 \times 0.8 = 8000$ c.m. $1.00 \div 0.8 = 1.25$ ohms

Starting once more from No. 10, since three sizes change doubles the section and halves the resistance, No. 7 has a section of 20,000 c.m. and 0.5 ohm resistance per 1000 ft. Starting from this and using 0.8 as a multiplier or divisor the data for Nos. 8 and 6 are secured. In forming the table the important fact is that the section and resistance halve or double every three sizes, the 0.8 relation will only hold for a very limited range.

Considering the fact that in commercial practice varying conductivity and temperature both affect the result, it will be plain that the approximate values are amply good enough for ordinary use.

218. Insulated Wire.—Most wire used in inside construction is rubber-covered. This rubber is really a mixture of pure Para rubber, washed and then mixed with metallic oxides, talc or other earthy matter and perhaps some waxes such as ozokerite, ceresin or oxidized oils or resins. The coloring matter is white or red lead, or lamp black. A very important addition is 2 or 3 per cent. of sulphur which vulcanizes the rubber compound after it has been put on the wire. The rubber compound is thus made firm and tough while it remains flexible. Probably not more than 15 per cent. of the whole compound is rubber in the kinds commonly used. The wire is tinned and then covered by passing it through a machine in which a plunger forces the compound through a die at the center of which the wire is guided through and after being covered is received on a reel. The covered wire is then placed in a steam-heated closed vessel at a temperature high enough to produce vulcanizing. It is then covered with cotton braided on, often in a double layer, and afterward soaked in a waxy compound to fill the braid and make the rubber cover more thoroughly water and weatherproof. For data regarding thickness of insulation, tests to which it may be subjected, etc., the reader is referred to the National Electrical Code. This is a set of rules and requirements regarding electric wiring and apparatus issued by the National Board of Fire Underwriters through their local representatives and inspection bureaus. The rules are concurred in by all important electrical associations of the country.

219. Installing Wiring.—The installation of wire is done by one or the other of four plans.

(*a*) *In Open Work.*—The wires are in plain view supported on porcelain cleats or knobs.

(*b*) *In Knob-and-tube Work.*—This is the usual method in ordinary house construction. The wires are carried through floor joists and studs in porcelain tubes; and in the same directions as they run on porcelain knobs.

(*c*) *In Moulding Work.*—The wires are laid in grooves cut in wood and over them a covering strip is nailed or screwed. In metal moulding both sides of the circuit are placed in the same runway.

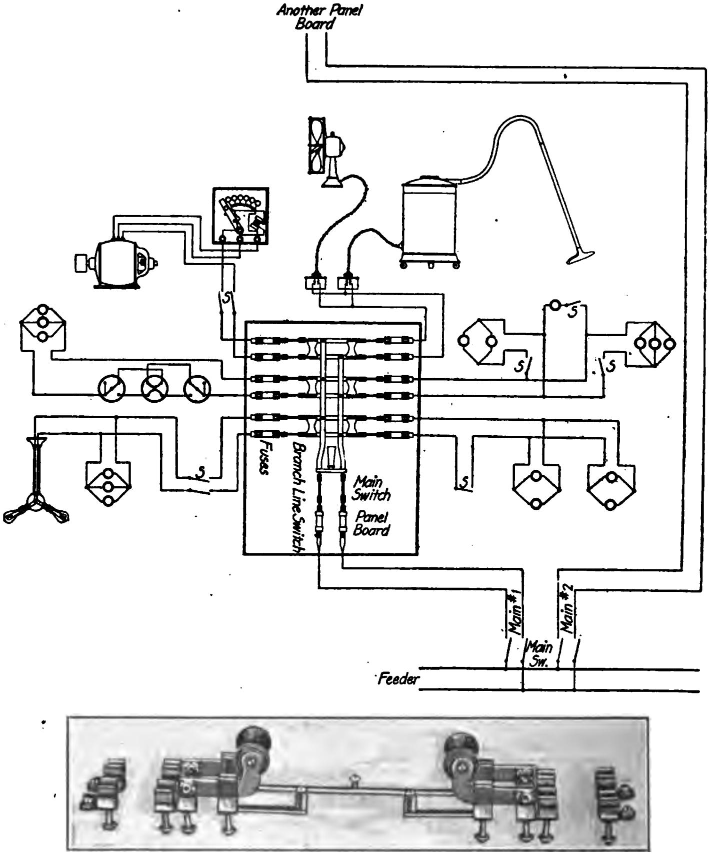


FIG. 310.—Lower part of figure shows construction and arrangement of the switches and fuse holders on the board.

(*d*) *In Conduit Work.*—Iron pipe with smooth interior finish forms the pathway through which the wires are drawn to iron outlet boxes where fixtures, switches, etc., are connected. This sort of construction is used in basements and in all fireproof buildings.[1]

No matter which method of construction is used, one or the other general plan of making connections is used. The one most commonly used is the panel-board system. Fig. 310 shows the principle of such a system. In it the supply is carried by mains to some central location at which a panel board is installed. Here all fuses are located and from it all branches run to the rooms where current is used, often branching without fuses, each branch circuit serving apparatus using no more than 660 watts.

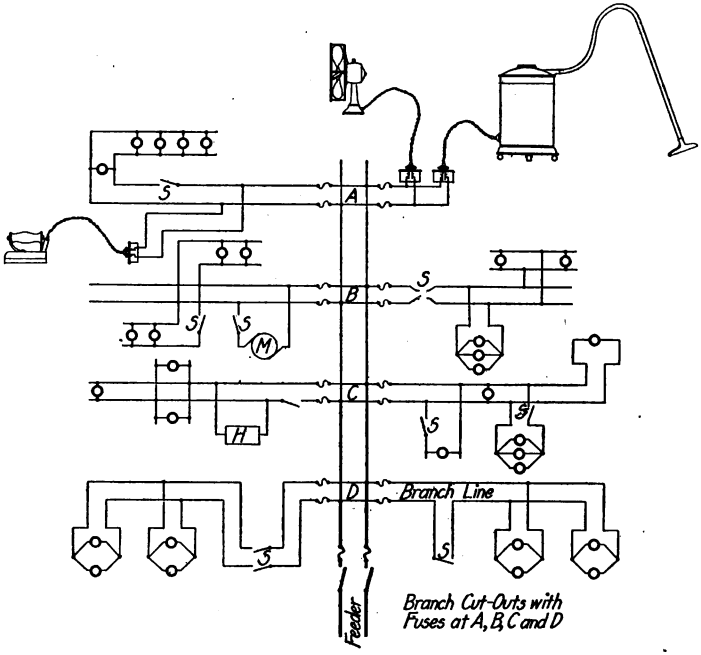


FIG. 311.

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[1] This book is not written to explain anything about practical wiring construction. For this the reader is referred to pp. 399—588 of the American Electrician's Handbook.

The tree system as shown in Fig. 311 is specially adapted to open wiring. A feeder is tapped by mains and these in turn by branches, cut-outs being installed at each branching point.

220. Rise in Temperature of Wires in Service.—A rise in temperature is produced in every wire carrying current. Should it be impossible for any heat to escape, no matter how small the current, eventually the wire would rise in temperature to the melting point. In the practical case the final temperature is reached when the heat dissipated per second is equal to the amount of heat generated per second due to the flow of current. The rise in temperature is regulated by the amount of current, by the size and conductivity of the wire and by the temperature of its surroundings and their character.

Long ago the current was determined experimentally which would raise the temperature of a wire 18°F. The values below were those determined for insulated wire buried in wooden mouldings. Such a current when doubled would cause the temperature to rise 75°F.

Size	Amperes	Size	Amperes
0000	174	9	21.6
0	103	12	12.8
3	61	15	7.6
6	36	18	5.1

The amount of current which it is safe to carry in house wiring is prescribed by the National Electrical Code. The figures are reproduced below for convenience in problem work. In conduit and exposed wiring the heat is dissipated more readily than when in moulding; hence with figures more liberal than in the table above the rise in temperature corresponds fairly well. Every electric circuit is supposed to be designed with a factor of safety of 2. That is so that under doubled current no dangerous rise of temperature will occur in the wiring.

B. & S. gage	Table A, rubber insulation, amperes	Table B, other insulations, amperes	Circular mils	Table A, rubber insulation, amperes	Table B, other insulations, amperes
18	3	5	200,000	200	300
16	6	10	300,000	275	400
14	15	20	400,000	325	500
12	20	25	500,000	400	600
10	25	30	600,000	450	680
8	35	50	700,000	500	760
6	50	70	800,000	550	840
5	55	80	900,000	600	920
4	70	90	1,000,000	650	1,000
3	80	100	1,100,000	690	1,080
2	90	125	1,200,000	730	1,150
1	100	150	1,300,000	770	1,220
0	125	200	1,400,000	810	1,290
00	150	225	1,500,000	850	1,360
000	175	275	1,600,000	890	1,430
0000	225	325	1,700,000	930	1,490
			1,800,000	970	1,550
			1,900,000	1,010	1,610
			2,000,000	1,050	1,670

221. The National Electrical Code.—This code is designed to so regulate the installation of electrical apparatus that no fire risk can develop. Fire risk is caused mainly by overheated conductors and by defective insulation. Everyone who has anything to do with the installation of electrical apparatus should have an up-to-date set of rules. Certain ones must be known in order to intelligently calculate wire sizes to be used. Inside work only will be referred to in the few here summarized.

Wires must not be of smaller size than No. 14 B. & S. gage (Rule 16*a*) except in fixture work when they may not be smaller than No. 18 B. & S. gage (Rule 26*v*). This provision gives wires in branch lines sufficient mechanical strength and makes it possible to replace a lamp by any household appliance without overheating the wires. Flexible cords also must be stranded and not have smaller cross-section than No. 18 (Rule 54*a*).

After passing the last fuse on a branch line no set of small motors, small heating devices or incandescent lamps, whether grouped on one fixture or on several fixtures or pendants (nor more than 16 sockets or receptacles) may take more than 660 watts (Rule 23*d*). Certain special conditions, however, are recognized in the same rule.

Motor leads must be designed to carry a current at least 25 per cent. greater than that for which the motor is rated (Rule 8*b*).

222. Drop in Wiring.—On a constant-potential circuit it is impossible to deliver to the current-using apparatus as many volts as are found at the sending end of the line. The current must flow through the resistance of the line wires and experience that drop in potential indicated by the product IR there. The volts delivered will be the volts at the sending end, less the line drop. In designing a line it is necessary to select some reasonable drop and determine what size the wire must be to satisfy the conditions. Custom demands that a line be designed for full-load conditions.

The drop allowed varies according to the kind of apparatus used on the system and the kind of load carried. On incandescent lighting circuits the closest sort of regulation is required for satisfactory results and so the drop is made small. On a small installation of a few lamps it might be 2 per cent.; on a larger installation 3 or 4 per cent. In a large building where the lights are not all on at once it might be 5 per cent.; putting 2½ per cent. drop in the feeders, 1½ per cent. in the mains, and 1 per cent. in the lamp circuits.

The real drop varies with the current used; and so on a large installation the computed drop is never found.

223. Calculating Wire of Proper Size.—Ohm's law can be used directly and is as good as any rule for calculating wiring. From $R = \frac{E}{I}$ we compute the resistance of the wire which gives the desired drop; then find what the resistance of 1000 ft. of this would be and thus find what size it is. The following example will make it clear.

Wires are to be taken along a route 135 ft. long to serve fifty ½-amp. incandescent lamps. The circuit is 110 volts, constant-potential, 2 per cent. drop is allowed.

The 50 lamps use 25 amp.

$$R = \frac{E}{I} = \frac{2.2}{25} = 0.0808 \text{ ohm.}$$

This is the resistance of 270 ft. of wire (135 ft. length of the route). Hence

$$\text{Resistance of 1000 ft.} = \frac{0.0808}{270} \times 1000 = 0.299 \text{ ohm.}$$

This lies between the resistance of a No. 4 and a No. 5 wire. No. 5 will give a little more than 2 per cent. drop, No. 4 much less. The carrying capacity of either size is abundantly great (see table). No. 4 would commonly be used.

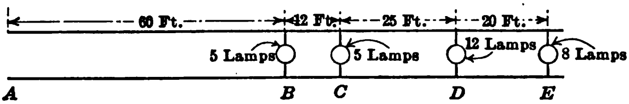


FIG. 312.

Very often the lamps are not bunched and the current is not delivered all at one place as in the above problem. In such cases the drop is figured to the center of distribution (c. of d.). The method is best illustrated by example.

In the above figure electroliers are placed at distances shown along a constant-potential line. At *A* the current is supplied; at *B* there are five ½-amp. lamps connected in parallel; at *C* another five; at *D* twelve; at *E* eight.

$$\begin{array}{rcrcrl}
5 \text{ lamps} & \times & 60 \text{ ft.} & = & 300 & \text{lamp-ft. to } B \\
5 \text{ lamps} & \times & 72 \text{ ft.} & = & 360 & \text{lamp-ft. to } C \\
12 \text{ lamps} & \times & 97 \text{ ft.} & = & 1164 & \text{lamp-ft. to } D \\
8 \text{ lamps} & \times & 117 \text{ ft.} & = & 936 & \text{lamp-ft. to } E \\
\hline
30 \text{ lamps} & & & & 2760 & \text{lamp-ft.}
\end{array}$$

The number of feet to the center of distribution is found from $\frac{2760}{30}$ = 92 ft. If the line is for 115 volts and 1 per cent. drop is allowed

$$R = \frac{1.15}{15} = 0.0766 \text{ ohm in 184 ft. of wire}$$

$$R \text{ per 1000 ft. of wire to use} = \frac{0.0766}{184} \times 1000 = 0.416 \text{ ohm.}$$

The proper size is then No. 6 run all the way through from A to E. It will carry safely 50 amp. and so will not overheat.

The method of calculating the distance to a c. of d. is to find a distance at which if all the lamps were placed, a drop the same as that demanded by the problem will be found. *Multiply the number of lamps at each point by its distance from the feeding point. Add together the various products (lamp-feet) and divide the sum by the total current to be delivered. The quotient is the distance to the c. of d. (center of distribution).* In a great many cases the c. of d. can be determined by inspection. Thus if three fixtures are placed at 15-ft. intervals along a line each carrying the same number of lights, the distance from the supply to the first being 45 ft., the distance to the c. of d. is 60 ft.; the same as that to the middle fixture. When it is specified that on a line the drop to the last lamp is to be a stated per cent. a calculation for proper wire to the center of distribution will give the correct result.

224. Calculation by Circular Mils Formula.—A formula much used for computing wire size is the following:

$$\text{Circ. mils section} = \frac{20.74 \times L \times I}{E}$$

in which E = volts drop in the circuit; I = amperes flowing in the circuit; L = length of run of circuit in feet, or half the length of wire used. The number in the formula differs slightly in different handbooks. It is twice the resistance of a wire having one circular mil section, 1 ft. long.

The following shows that the rule is a correct one. The resistance of conductors varies inversely with their cross-section. Let R be the resistance per foot of a conductor it is proposed to use in a line whose cross-section in circular mils is X. Then

$$\frac{R}{10.37} = \frac{1}{X} \quad \text{or} \quad X = \frac{10.37}{R} \qquad (a)$$

If the wire is used as part of a lighting circuit

$$R = \frac{\text{Resistance of the wire in circuit}}{\text{Length in feet of the wire in circuit}} = \frac{R_c}{2L}$$

But $R_c = \dfrac{E}{I}$ for the wire of the circuit. Hence

$$R = \frac{E}{I} \times \frac{1}{2L} = \frac{E}{2LI}$$

Putting this value of R in formula (a)

$$X = \frac{10.37}{\frac{E}{2LI}} = \frac{10.37 \times 2LI}{E} = \frac{20.74\,LI}{E}$$

The use of the formula may be illustrated by a problem.

50 kw. of electrical power at 250 volts is to be carried over a route 190 ft. long with a drop of 2 volts. Find the proper cable to use

$$\text{c.m.} = \frac{20.74 \times 190 \times 200}{2}$$
$$= 394{,}060.$$

Use a 400,000-c.m. cable which is also able to carry 325 amp. and so safe on carrying capacity.

In many problems the number 22 can be substituted for 20.74 and the calculations be made more easily while the size of wire to be used comes out approximately the same. On 110-volt circuits, for example, the denominator is often 2.2 which divides evenly into 22. Illustrations of this appear in later problems.

225. Calculation of Complete System.—In a system including mains and branches it is usually necessary to select the drop allowed in the mains and in the branches in order that a total drop of given amount shall be secured.

When the distribution is by the panel system, the calculation is simple; for the drop in the main is calculated to the panel board, and the branches are each figured separately. Thus suppose on a 110-volt circuit a main runs 150 ft. to a panel board, from which there are 10 branches each carrying lights which use 5 amp. Suppose one of the branches (A) measures 100 ft. to the c. of d. and another one (B) 60 ft. If a total drop of 3 per cent. is allowed, it may be wise to put 1 per cent. in the branches and 2 per cent. in the mains.

The sizes would be determined thus:

Main.—Circ. mils $= \frac{22 \times 150 \times 50}{2.2} = 75{,}000$

Use No. 1 wire (carrying capacity 100 amp.)

Branch A.—Circ. mils $= \frac{22 \times 100 \times 5}{1.1} = 10{,}000$

Use No. 10 wire (carrying capacity 25 amp.)

Branch B.—Circ. mils. $= \dfrac{22 \times 60 \times 5}{1.1} = 6000$

Use No. 12 wire (carrying capacity 20 amp.).

Other branches would be calculated in a corresponding way.

Often the length of branch lines, or current used on them, or both, is so small that the minimum size No. 14 must be used. In such case the calculation should be made by calculating the drop in the branches first and then putting the remainder in the mains. The plan is illustrated in the next example.

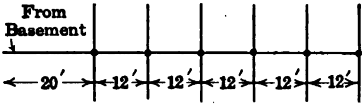


FIG. 313.

A main runs from the switchboard in the basement of a building to the second floor 35 ft., and then down a corridor serving rooms with lights as shown by Fig. 313. Each branch runs 25 ft. to a c. of d. in a room where the use of current amounts to 4 amp. on a 110-volt system. On any branch the drop will be as follows if No. 14 wire is used.

R of 50 ft. of No. 14, 0.125 ohm.

$E = IR = 4 \times 0.125 = 0.5$ volt gone.

If each branch line is made of No. 14 wire, for 2 per cent. drop in the system we may put $2.2 - 0.5 = 1.7$ volts in the main which has a c. of d. 170 ft. from the supply. The proper size for it is then calculated.

$$\text{Circ. mils} = \frac{22 \times 170 \times 48}{1.7} = 52{,}800$$

Use No. 3 which has 50,000 c.m. and will make the total drop slightly more than 2 per cent. (carrying capacity 80 amp.).

226. Wire size to D.C. Motors.—The calculation is made precisely as for lights except that the wire must be so selected that its carrying capacity is right for 25 per cent. overload while the drop is calculated for full load. Since a larger drop than for a lighting circuit is often permitted, the size in many cases is settled by the Code. It is important to remember that the current to a motor is that which will enable it to develop the power by which it is rated, allowing for its efficiency. The following are conservative values of motor efficiency and apply at full load.

Horsepower	Efficiency
⅛	50
¼	60
1	70
5	80
10	85
50	90

An example will show how to apply these values.

A 5-hp. shunt motor is to be supplied with current from a 250-volt circuit. The length of run to the motor is 100 ft. and 3 per cent. drop is allowed.

5 hp. = 5 × 746 = 3730 watts developed
3730 ÷ 0.80 = 4162 watts must be supplied at full load
4162 ÷ 250 = 16.6 amp.

$$R = \frac{7.5}{16.6} = 0.452 \text{ ohm in 200 ft. of wire}$$

or 2.26 ohms per 1000 ft. This is slightly more than the resistance of No. 13; but No. 12 must be used as the nearest trade size available. At 25 per cent. overload the motor takes 20.7 amp. and No. 12 is just able to carry this if insulated with rubber.

227. Three-wire System Wiring.—Three-wire lines are widely in use in distribution systems but they are usually carried only as far as the mains run. The branch lines for lights are two-wire; tapped either to positive or neutral, or to neutral and negative. Motor lines, except for very small motors, are two-wire lines from positive and negative.

The two-wire branch lines are calculated by methods already explained. Some preliminary statements will make clear the method of calculation given in the next paragraph. If one hundred ½-amp. lamps were connected in parallel on a two-wire system, 50 amp. will flow in each line. If the same lamps were connected on a three-wire system as a balanced load, only 25 amp. will flow in the positive and negative and none in the neutral. This would make the three-wire positive and negative lines half the section (double the resistance) for the same drop as in the corresponding two-wire line. But the per cent. drop is properly kept the same for the same results at the lamps, and in the three-wire system the line voltage is doubled. Hence when the hundred lamps are put on a three-wire line the section of wire to use in positive and negative is only quarter as much as when they are connected to a corresponding two-wire line. Take 110-volt lamps and note the following for the above. The main is 200 ft. long and 2 per cent. drop is allowed.

two-wire line

$$\text{c.m.} = \frac{22 \times 200 \times 50}{2.2} = 100{,}000$$

three-wire line

$$\text{c.m.} = \frac{22 \times 400 \times 25}{4.4} = 25{,}000$$

In calculating mains, therefore, select the per cent. drop and find the c. of d. as for a two-wire system. Count the lights to be supplied and use half the current they take on a two-wire line in the calculation. The number of volts lost is the proper per cent. of the voltage from positive to negative and not that each lamp receives. After finding the proper size select the neutral. Usually it is the same section as either main, but occasionally it is twice the section of either of them. Consideration of a diagram will show that the amount of current flowing in the neutral might be as much as in positive or negative. One case would be when the lights on one side only are in use. If there is a chance that the system might be sometime supplied from a single dynamo the neutral must be double the section of the other wires or the drop on the system will be abnormal. Fig. 314 shows how this would be. As a three-wire system no current would flow on the neutral when six ½-amp. lamps were in use, but when used two-wire, 3 amp. flow in it.

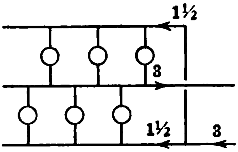


Fig. 314.

From a certain panel board there are supplied on 20 two-wire lines one hundred and twenty 25-watt lamps. The main is three-wire from a 250-volt supply (125 volts each side). Two per cent. drop is allowed in it. It is brought over a route 180 ft. long.

On a balanced load 12 amp. would flow in positive or negative. The size is then determined by

$$\text{Circ. mils} = \frac{20.74 \times 180 \times 12}{5} = 8959$$

No. 10 wire will be right. The neutral may be No. 10 for three-wire requirements or No. 8 (better No. 7) if a change over to two-wire distribution is anticipated.

228. Special Notes on Wiring.—It will have been inferred from the various problems and discussion of wiring preceding this, that in making calculations no account is taken of switch or fuse resistance or of fixture wiring. They are all assumed to be so small that they may be neglected.

On branch lines arrangements should always be made to use no wires larger than No. 12 if there is need of clamping them under the terminal connections of switches, cut-outs, receptacles, etc. Such terminals are not adapted to carry larger wires.

To facilitate changes in wiring to meet necessary conditions including the cost of wiring the following should be noted.

(*a*) The drop on a line is doubled if the section of the wire used is halved.

(*b*) If the length of a run is altered, the section of wire must be changed in the same proportion to keep the drop unchanged.

(*c*) A change in the e.m.f. used on a line will for the same per cent. drop change the necessary section of wire in inverse proportion to the square of the e.m.f. used. Thus, if we use 220 volts rather than 110, the section of wire used may be made one-quarter as great for the same watts supplied.

(*d*) When the calculated size comes halfway between two commercial sizes, one leg of the circuit may be run of one of these and the second of the other. The trouble involved in taking two reels of wire to a job, however, usually makes this plan undesirable.

It may be well at this point to call attention to the fact that the method used in calculating c. of d. for lights may be applied to circuits on which there are motors or any industrial appliances. The plan is simply to substitute ampere-feet for lamp-feet in the calculation and work the problem as in section 223.

229. Central Station Lines.—Such lines are not usually calculated as are those for indoor circuits. On some parts of the system, as in a network (see section 77) where all customers are to be supplied with the same voltage, the drop must be kept low and the lines would be figured for small loss but not for full current demand of connected apparatus. Experience shows that not nearly all the connected load is ever in use on even a single part of a network. On feeders, engineering questions of cost of the investment and value of the power lost must be considered. Constant potential on the network is maintained by regulation at the station to procure the proper value at "feeding in" points. Other books must be consulted for methods of procedure.

230. Railway Wiring.—Railway wiring is harder to calculate than that for lighting, since the location of cars and amount of current demand is not only shifting but irregular. The problem is similar to central station distribution in that considerations of value of the investment, etc., are involved. The trolley wire or third rail is planned largely with a view to wearing qualities and strength. When using a method of distribution like that shown in Fig. 95 some companies plan each section by placing cars in the most unfavorable position, calculate the current for each, and arrange the length of section so that maximum permitted drop occurs, using one standard size of feeder.

The track return and bonding along the track must be planned so that the drop there shall be so low and so distributed that current in dangerous amounts does not flow in, to, or from underground pipes or cable sheaths. Supplementary copper return feeders are often run in large systems.

Car wiring is commonly planned with a view to adequate current-carrying capacity and mechanical strength. The drop is too small to count.

231. Wiring of Series Circuits.—Arc lamps and many incandescent-lamp circuits for street lighting are series circuits as already outlined in sections 135, 211, 215. On a series circuit the light in the furthest lamp is as bright as one near by without regard to the drop in the line. Wires are therefore selected mainly for mechanical strength, that is, to stand through winter storms. No. 8 or 7 or 6 wire is commonly used.

232. A.C. Wiring—General.—At the beginning of Chap. X it was shown that Ohm's law did not hold for alternating-current circuits, and since the whole plan of calculation of wiring outlined in this chapter is based on Ohm's law it is important to see whether any of it can be used when the current flowing over line wires is alternating.

Every A.C. line has inductance since it forms a loop and when the current is varying in it the flux through and around it is varying. Every one has also a property known as capacity (ability to hold charge) which it has been unnecessary to discuss in this book. The inductance of a line is greater when the wires are separated; the capacity is greater when they are close together. Unless either or both these properties and their effects are so small that they can be neglected, an entirely new method of calculation must be set forth. Such things cannot be neglected in the design of long, heavy or high voltage lines. The engineering problems involved in their design are complex and will not be taken up here.

When A.C. flows through a wire the current is not evenly distributed over its section, but is stronger toward the surface. This effect is known as the skin effect. At usual frequencies and for conductors less than ½ in. in diameter it need not be counted.

Keeping to the consideration of lines no longer than those used in ordinary house and factory distribution, calculation will be easy when a number of details have been explained.

233. Single-phase Wiring.—In A.C. wiring the volts lost in a line and "the drop" are not necessarily the same. By the drop we always mean the difference between the volts on the load and those supplied at the sending end of the line.

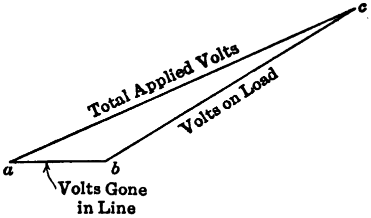


FIG. 315.

In section 118 it was shown how two e.m.fs. in the same circuit combine to give a total which may or may not be the same as that amount secured by adding them together. In a circuit made up of connecting wires and apparatus, the e.m.f. on the apparatus and that used to send current through the line are such. Fig. 315 shows how they may relate. It is clear that the volts gone in the line are more than the difference between total applied volts and volts on the load. As a connected load becomes more inductive the diagram of this figure would change by point *c* moving counterclockwise around *b*. If the load is non-inductive it moves further around clockwise and the line *bc* may simply be an extension of *ab*. In this connection it is well to remember that the current in the wires and the load has the same amount everywhere at a given instant. The current has the same phase all the way around.

As already suggested, in ordinary house and factory wiring the troublesome factors in line calculation may be neglected. Consider the following problems.

A feeder following a route 60 ft. long serves a panel board to which incandescent lamps are connected, using 15 amp. on branch circuits. The supply is from a 110-volt, 60-cycle A.C. line and 2 per cent. drop is allowed.

$$\text{Circ. mils} = \frac{22 \times 60 \times 15}{2.2} = 9000$$

If D.C. current were used No. 10 wire would be right (carrying capacity 25 amp.). For A.C. the same size will be right because lamps are non-inductive and the special properties of the line are too small to influence the result. The use of 22 in formula rather than 20.74 and the choice of a wire having 10,000 rather than 9000 circ. mils will much more than compensate any A.C. effects.

A 5-hp. single-phase, 250-volt, 60-cycle, A.C. motor which operates at full load on a power factor of 0.7 is to have the wiring for it calculated. The line runs 135 ft. and 2 per cent. drop is allowed.

5 hp. × 746 = 3730 watts

0.80)3730 watts developed

0.7)4662.5 watts supplied

250)6660 volt-amp. supplied

26.6 amp. full-load current to motor.

$$\text{Circ. mils} = \frac{22 \times 135 \times 26.6}{5} = 15{,}800$$

This indicates No. 8 wire (carrying 35 amp.) which is good for a 25 per cent. overload, and this should be used for the reasons stated in the previous problem.

As the size of the wires required for transmission get larger the possible inaccuracy of a result thus computed increases. On wires larger than No. 4 it is well to install one size larger than calculated; and when a calculation shows a need for wires larger than No. 0

an exact calculation should be made taking account of the various factors properly.

234. Polyphase Wiring.—The methods to use in calculating the proper size of wire to use on polyphase lines are stated below and their truth illustrated. In all the illustrations lamp load is assumed. The principles hold in such a way that if the proper size to carry the load single-phase has been determined (by exact methods if necessary, not given above) the proper size for polyphase distribution may be deduced by using the methods following.

To calculate the *proper wire size for single-phase distribution* *proceed* as for D.C. work.

Illustrations are given in the preceding section, or by the following. The drop is made very large to make relations clear.

Twenty-four amperes are sent over a 500-ft. line of No. 7 wire (½ ohm per 1000 ft.) with a drop of 12 volts (Figs. 316 and 317).

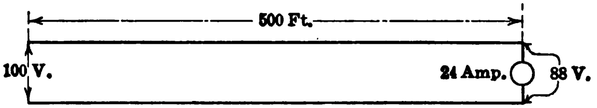


Fig. 316.

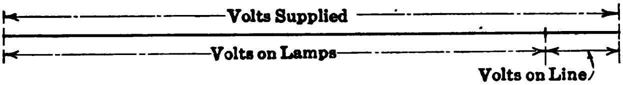


Fig. 317.

The proper wire size for *two-phase distribution using a four-wire line* is obtained by giving each wire half the cross-section it would have for an equivalent single-phase distribution.

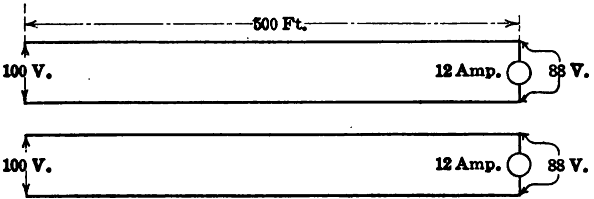


Fig. 318.

A four-wire two-phase line is shown above (Fig. 318) for the same lot of lamps as on the single-phase line. In order to fulfil the conditions

No. 10 wire (1 ohm per 1000 ft.) must be used, which has half the cross-section of No. 7.

The proper size wire for *two-phase three-wire lines* is secured if each wire is given half the section required for the equivalent single-phase distribution.

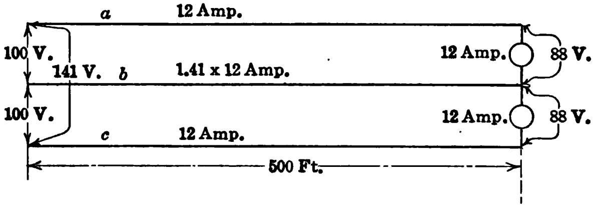


FIG. 319.

A three-wire two-phase line is shown above (Fig. 319) for the same lot of lamps as on the single-phase line. In order to fulfil the conditions No. 10 must be used.

The current in wire *b* is made up of that in *a* and that in *c* combined. They have 90° difference of phase with each other and so the current in *b* is 45° out of phase with either one (see Fig. 187 and principles in the paragraph which contains it). The following figure (320) therefore represents, the conditions, numerical values being derived thus:

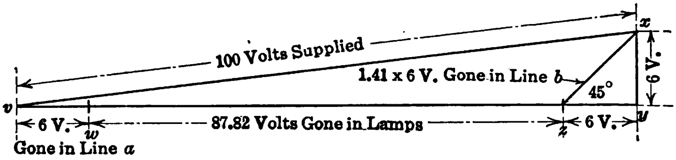


FIG. 320.

Volts gone in $a = \frac{1}{2}$ ohm $\times 12 = 6$

Volts gone in $b = \frac{1}{2}$ ohm $\times 12 \times 1.41 = 1.41 \times 6 = 8.46$

The little triangles *xyz* is a right-angled triangle and each side (starting from 1.41×6) must have the lengths marked on it. The length of the line *vy* may be determined as follows.

$$\sqrt{100^2 - 6^2} = \sqrt{9964} = 99.59$$

subtracting the lengths *vw* and *xy* we have

$$99.82 - 12 = 87.82$$

which is very close indeed to the 88 volts marked on Fig. 319.

The proper wire size for *three-phase three-wire lines* with mesh connection is secured if each wire is given half the cross-section required for the equivalent single-phase distribution.

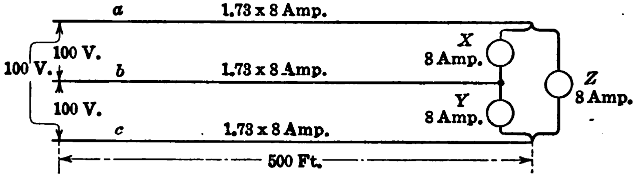


Fig. 321.

The same lot of lamps as before are here shown (Fig. 321) redistributed for a three-phase line. We will make it No. 10 wire and find that the drop comes as marked.

For reasons which it is unnecessary to restate, the current in the lines *a*, *b*, *c* are the amounts marked and are out of phase with the currents as in *X*, *Y* and *Z*. The current in *a* is made up of that in *X* and *Z*, combined as in Fig. 204. This causes the volts gone in *a* to be out of phase with those in *X* and still more out of phase with the volts gone in *b*. The relations are shown in Fig. 322 below.

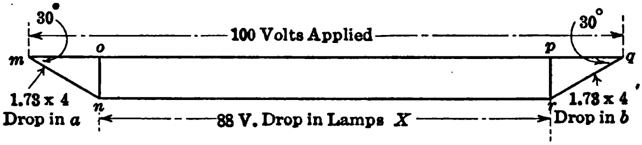


Fig. 322.

Volts gone in *a* or *b* = ½ ohm × 1.73 × 8 = 1.73 × 4 = 6.84. It can be shown that in a triangle like *mno* the side *mo* is 0.866 the length of the side *mn*. Hence

$$mo = 1.73 \times 4 \times 0.866 = 1.5 \times 4 = 6 \text{ volts}$$

when *mo* and *pq* are subtracted from the whole length *mq* (representing 100 volts of applied e.m.f.) we get

$$100 - 12 = 88 \text{ volts} = \text{length } nr = \text{drop in lamps } X$$

The proper size wire for *three-phase four-wire lines* with star connection is secured if each wire is given one-sixth the cross-section required for the equivalent single-phase distribution.

On the line *a* (Fig. 323) the drop to the neutral *N* at *d* through the lamp is 100 volts. If 88 of this is on the lamp, 12 volts is lost in the line *a*. The resistance of line can then be obtained.

$$R = {}^{12}\!/_{8} = 1.5 \text{ ohms.}$$

Resistance and cross-section of conductors vary inversely. No 7 was used for single-phase distribution. Hence

$$\frac{R \text{ of } 500 \text{ ft. No. } 7}{R \text{ of } 500 \text{ ft. of wire to use}} = \frac{\text{section of wire to use}}{\text{section of No. } 7}$$

$$\frac{0.25}{1.5} = \frac{\text{section of wire to use}}{\text{section of No. } 7}$$

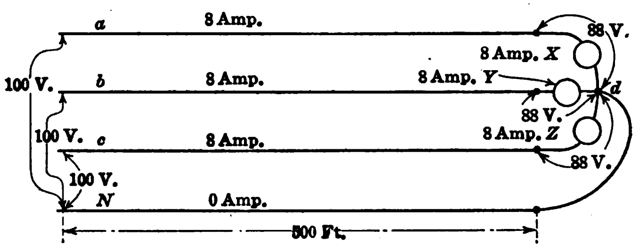


FIG. 323.

Multiplying numerator and denominator each by $\frac{2}{3}$ we have

$$\frac{\frac{1}{6}}{1} = \frac{\text{section of wire to use}}{\text{section of No. } 7}$$

The neutral is made the same size as the others since on unbalanced load it may carry as much current as any of them.

QUESTIONS AND PROBLEMS

1. (*a*) Starting from No. 0000 with a diameter of 0.46 in., and using the multiplier given in section 216 find the exact diameter of No. 00 wire. (*b*) Calculate the circular mil section of No. 00 from its diameter, and compare with the cross-section given in section 217.

2. A certain alloy wire has a cross-section of 225 c.m. and a resistance per foot of 2.16 ohms. Another wire of the same alloy has a diameter of 0.03 in. What is its resistance per foot?

3. Using the formula in section 217 for calculating *R* per 1000 ft.

calculate the resistance per 1000 ft. of No. 10 copper wire having 97 per cent. conductivity.

4. Calculate the sectional area of a cable made up of 91 wires each No. 14 in size. Calculate the resistance of 1000 ft. of this cable.

5. (*a*) How could the resistance of a cable made of 61 No. 8 wires compare with that of one made of 192 No. 16 wires? Neglect any effect of spiralling the layers. (*b*) Would you select a No. 000 wire or a cable of 37 No. 13 wires in preference for low resistance?

6. Calculate the proper size of wire to use for each of the following cases. Remember that drop, heating or size permitted by the Code may determine the answer. The incandescent lights in each case take ½ amp.; the circuit is 110-volts D.C. constant-potential. Use Ohm's law method.

(*a*) 40 lamps 100 ft. away (200 ft. of wire), no more than 1 per cent. drop allowed.

(*b*) 60 lamps 20 ft. away, 3 per cent. drop allowed.

(*c*) 4 lamps 80 ft. away, 2 per cent. drop allowed.

7. A certain line is to be carried along a route 125 ft. long (250 ft. of wire) to supply a lot of one hundred ½-amp. incandescent lamps. (*a*) Calculate the proper size of wire for 1 per cent. drop, the system being 110 volts D.C. (*b*) What size for 2 per cent. drop? (*c*) For 3 per cent. drop? (*d*) For 4 per cent. drop? [Work part (*a*) by c.m. formula. Other parts by inspection of this answer and writing down the result.]

8. A certain main carries 50 amp. at 100 volts D.C. The line follows a route 400 ft. long and is of No. 1 wire. How many volts at the receiving end? How many per cent. drop? If the distribution were changed to 200 volts and the same power transmitted, what size wire for the same per cent. drop? Does this verify the statement under *c* in section 228?

9. The mains from a 100-kw. dynamo at 125 volts D.C. are allowed 1 volt drop to the switchboard. What size wire must be used? 50 ft. is the length of run from machine to switchboard. Note that if the necessary weight of copper used be alone considered, it will be more economical to use two cables in parallel for each lead.

10. A large electrolier over the center of an Auditorium has in it 52 lights (½ amp. each). The stem of the electrolier is 30 ft. long. No. 10 wires pass through this. The route of the line is across the attic and directly down to the switchboard in the basement 125 ft. What size of wire shall be used to limit the total drop to 3 per cent.? Take the resistance of the wire in the fixture stem into account, the supply being 115 volts D.C.

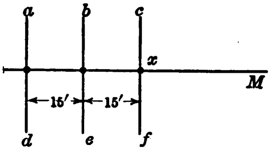
11. Five 5-amp. enclosed constant-potential D.C. arc lamps are placed along a station platform 25 ft. apart. They are supplied from 110-volt D.C. mains through a switch in the station 60 ft. from the first lamp. What size of wire shall be used for 2 per cent. drop?

12. In a certain mill the wiring is exposed on knobs. A 250-volt D.C. circuit is in use. A line is to be run to a 50-hp. motor 400 ft. Four per cent. drop may be allowed. What size of wire shall be used?

13. A run of wire is taken 200 ft. to a panel board from which there is supplied a 2-hp. motor, five 5-amp. arc lamps, and fifty ½-amp. incandescent lamps. The circuit is 110 volts D.C. and 2 per cent. drop is allowed in this main. What size of wire shall be used?

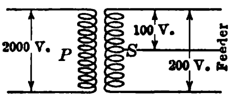
14. Two ventilating motors are in the attic of a three-story building. Each one is for 2 hp. and they are supplied through a panel board in the attic from which to one motor it is 10 ft. and to the other 25 ft. by the route the wires take. From switchboard in the basement to the vertical run is 40 ft.; vertical run is 80 ft.; distance in attic to location of panel board is 40 ft. Calculate the wiring for these motors on the basis of 4 per cent. total drop on a 110-volt D.C. circuit. The wiring is in conduit.

15. A certain auditorium is wired as shown. *M* is a main which runs through a distant control switch to the main switchboard. The whole distance is 160 ft. to the first branching point *x*. *a*, *b*, *c*, *d*, *e*, *f*, represent some of the branches. There are 10 on each side. The main *M* is carried exposed beneath the floor equally distant from both sides of the room. At each branching point like *X* is a double branch cut-out. Branch lines run exposed to the side walls and then turn up in conduit to side brackets at an average height of 15 ft. from the floor. The room is 60 ft. wide. Each side bracket has five ½-amp. lamps. The circuit is 110 volts D.C. Calculate the wiring, using 3 per cent. total drop to the lamps. (Make branches of No. 14 wire for a start.)

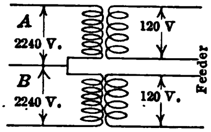


16. A certain three-wire D.C. feeder from central station service runs 240 ft. to a panel board. The line is 120 volts on each side. There are one-hundred and eighty 40-watt incandescent lamps and three 2-hp. motors supplied over it. The lights are on two-wire branches as a balanced load. The motors are across the outside lines. Calculate the wires for 2 per cent. drop and choose a neutral of such size that if the lights on one side were all on and others off the distribution would be satisfactory.

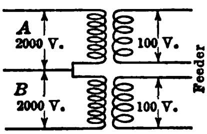
17. Sixty 100-watt Mazda lamps are supplied from a panel board on two-wire branches in an industrial building. The feeder supplying the panel board is three-wire single-phase A.C. at 60 cycles the feeder being connected to the transformer as here shown. Calculate the proper size for 2 per cent. drop, the length of run being 160 ft.



18. One hundred and forty-four 40-watt Mazda lamps are supplied from a panel board on two-wire branches in an industrial building. The feeder supplying the panel board is four-wire two-phase A.C. at 60 cycles, the volts on each phase at secondaries of transformers is 120 volts, the connections being as shown here. Show by diagram some proper panel board connections for two-wire branches and calculate proper size of wire for the feeder at 2 per cent. drop and 100 ft. length of run.



19. One hundred and twenty 40-watt Mazda lamps are on two-wire branches in an industrial building. The load is balanced as nearly as possible. The feeder supplying the panel board is three-wire two-phase A.C. at a frequency of 60. The volts on each phase at secondaries of transformers is 100, the connections being as shown here. Show by diagram some proper panelboard connections for two-wire branches and calculate proper size of wire for the feeder at 2 per cent. drop, the length of run being 90 ft.



20. A 10-hp., 220-volt, three-phase induction motor has an efficiency at full load of 85 per cent. and a power factor of 0.8. It is served by a three-wire line which runs as exposed work on knobs over a route 120 ft. long. What size of wire for it when a full-load drop of 2 per cent. is permitted? What current flows over each wire?

21. A lot of one hundred and forty-four 40-watt incandescent lamps are supplied on two-wire branches from a four-wire three-phase system with transformer secondaries star-connected. One hundred and twenty-volt lamps are used arranged as a balanced load. Calculate the size of wire to use for 2 per cent. drop. What current flows over each wire. The length of the run is 100 ft. Compare the result with that in problem 18; and for a check make a direct calculation.

22. A series A.C. circuit contains fifty 170-watt 7.5-amp. incandescent lamps for street lighting. If the line is served from a tub transformer and is 18,000 ft. long of No. 8 wire, what voltage at transformer terminals when all the lamps are burning?

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